Roadmap for Adopting 3D Concrete printing Technology for Production of Affordable Houses.

Master Thesis submitted to the Faculty of the Construction Management and Engineering of the University of Twente, in fulfillment of the requirements for the degree "Master of Science".

By

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ROADMAP FOR ADOPTING 3D CONCRETE PRINTING TECHNOLOGY FOR PRODUCTION OF AFFORDABLE HOUSES

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Preface:

By means of this research, I complete my two-year master program Construction Management and Engineering at the University of Twente, Enschede, Netherlands. This report gives the results of the research I conducted at University of Twente and along with the company Witteveen+bos during my 8-month master's thesis period. The research covers on the topic of developing roadmap for contractors in India for adopting 3D concrete printing to construct affordable houses process. To this end, roadmap is validated to be complete, usable, realizable, and adaptable for Indian contractors.

Before coming to Netherlands, I had a clear goal of studying and contributing to digital technologies in construction. Piece of article on my local newspaper back in India stating, “3D concrete construction is new way to build homes and that is happening in Netherlands in city of Eindhoven.” That became my motivation to pursue my masters in Netherlands and to learn the technology. Thus, with all the acquired knowledge along my master’s journey. My focus with the master thesis, I had clear goal on researching on integrating innovation into business application, which innovation of course happened to be 3D concrete printing. The process of conducting this research involved many experts from different disciplines, lots of initial unknowns, and was highly iterative. The lessons I learned therefore, are interestingly similar to what is required to bring 3D printing technology forward. Skills to manage uncertainty, looking across industry boundaries and disciplines, deal with the resulting conflicting perspectives, and bringing them together in a final deliverable. I think this approach embodies the spirit and added value of the MSc Construction Management and Engineering and have worked on this project with great enthusiasm.

The process of developing a business roadmap was not an easy task it required a lot of repetitive guidance and discussion with experts, Nevertheless, during my journey I learned a lot about road mapping and data that was needed from different stakeholders. The achievement of developing the roadmap was simply not possible with the support and freedom I received from Witteveen+bos, in particular to my supervisors Marijn Bruurs and Hans Laagland. Therefore, I would like to thank them for their advice, support, and trust, not only regarding my master's thesis, but also regarding moral support which was needed the most during the worst time that the world has seen due to COVID-19 pandemic. In this preface, I would also like to express a word of thanks to all key expertise for providing inputs that contributed to this master's thesis.

I would like to extend my thanks to Dr. Farid vahdati, my first supervisor at UT, thank you for believing and supporting me. Very first words said by you on first meeting was “I am there with you for complete support and guidance”. Throughout the research you continuously guided with your enthusiasm and way of providing feedback which allowed me to stay on track. You encouraged me to take charge of my project and gave feedback in a way that empowered me to build on my own ideas. Particularly in the initial phases when I was in an ocean of different perspectives this was extremely helpful and motivating. I thank my committee chairman, Dr J.T. Voordijk, for the clear advice during the formal milestone meetings. You added a sharp critical eye to the direction of the overall project and gave very clear feedback that was understandable. Your genuine interest in my opinion on the picking the particular road mapping strategies encouraged me to develop my individual perspective between the many experts I encountered.

I would like to express my heartfelt thanks to my father Prakash R Sonwalkar, mother Kavitha P Sonwalkar and my family members for their unconditional support for achieving my dreams. Last but importantly, I would like to thank all my friends for their endless support and motivation.

Contents

Abstract

Building mass affordable housing with adequate structural safety in a given period is very important in developing nations. New technology, for instance, 3D concrete printing technology, has the advantages of constructing affordable houses, for instance, an increase in architectural freedom. An increase in the speed of construction decreases labor dependency, minimizes the time & cost overruns, and thus has the great potential for constructing houses at low cost. Given such advantages and numerous research being carried out by many companies and research institutes around the world, we still do not see much technology adoption by the contractors in using it for constructing low-cost housing, which is need for an hour. A new country to research the problem context mentioned above is India. Since India has led to a shortage of 26-37 million of affordable urban homes (Indian development review, 2019), thus, initiating Pradhan Mantri Awas Yojana (PMAY- 2015), a "Housing for all" mission that promises to build 20 million affordable houses by 2022. Thus, the government of India has set a technology sub-mission (TSM) under the PMAY mission, which supports adopting new technology that would reduce the construction period, cost, waste and makes affordable housing construction more sustainable. As a result, 3D concrete printing technologies can be a promising solution under this technological sub-mission, which can open the way to mass customization in construction and can help achieve the construction of houses in a sustainable approach. However, 3D concrete is still a very new technology in the Indian construction industry. Thus, there is a need to understand the challenges & benefits associated with the adoption of 3D concrete printing by contractors in the Indian construction industry. Hence, in this research, the technology, environment, cost (TEC) framework is introduced as an understandable approach to assessing the current state of art, benefits, challenges, and opportunities of 3D concrete printing technology. Furthermore, with the inputs from the TEC framework, the road mapping framework has been developed for streamlining activities for adopting 3D concrete printing by contractors. The roadmap is widely considered as an appropriate approach for matching short-term actions to long-term goals to support technology management in the firm. Thus, road mapping enables firms to benefit the guiding of the adoption activities with possible to consider a wide range of possible future business environments than affordable houses. Thus, the results present the roadmap for Indian contractors to adopt 3D concrete printing technology, which to this end, roadmap application is validated to be complete, usable, realizable, easy to understand, and adaptable in the contractor's firm. In concluding, the research makes a major contribution and its impact on technology implication in the business environment, which gives the contractor enough scope to choose whether to head in this direction or not.

Key Words and abbreviations.

3D:- Three dimensions; 3DCP:- 3D concrete printing, TOE:- Technology, organization, and environment, PMAY:- Pradhan Mantri Awas Yojana; TEC:- Technology environment and cost; TPM:- Technology, Product and Market; BMTPC:- Building material and technology promotional council.

1 Introduction

1.1 BACKGROUND

According to UN figures, only 13% of the world's cities have access to affordable housing (UN HABITAT, 2016). Access to decent, affordable housing is so fundamental to the health and well-being of people and the smooth functioning of economies that it is embedded in the United Nations Universal Declaration of Human Rights (The McKinsey Global Institute, 2014). The idea of affordable housing recognizes the needs of households who pay beyond 30% of their gross incomes (Hulchanski David, 1995). McKinsey estimated that 330 million urban households around the world live in substandard housing based on current trends in urban migration and income growth. Moreover, by 2025, about 1.6 billion people would occupy crowded, inadequate, and unsafe housing. To replace today's substandard housing and build additional units needed by 2025 would require an investment of $9 trillion to $11 trillion for construction (The McKinsey Global Institute, 2014). Of this, $1 trillion to $3 trillion may have to come from public funding. Next to this, construction materials and the building sector are claimed to be responsible for more than one-third of global resource consumption, and up to 40% of urban solid waste is construction and demolition waste (Ellen MacArthur foundation & ARUP, 2019).

So far, in developing economies, the cities struggle with the challenges of providing housing at a reasonable cost for low and middle-income populations such as India. Where 31% of India's population lived in urban areas as per Census 2011, this number is expected to grow to 40% by 2030 with a contribution of 75% of India's Gross Domestic Product (GDP) (Ministry of Housing and Urban Affairs (MoHUA), 2019). Accordingly, with the rapid urbanization and the lack of planned affordable housing in India has led to a shortage of 26-37 million urban affordable homes (Indian development review, 2019). Affordable housing from the Indian context refers to housing units that are affordable by that section of society whose income is below the median household income (ET, 2018). Different income households of the society that have been identified by the Indian government that are eligible for affordable housing are shown in Table 1.

Furthermore, Affordable Housing has been one of the focus areas for the Indian government over the past few years. Thus, initiating Pradhan Mantri Awas Yojana (PMAY- 2015), a mission that promises to build 20 million affordable houses by 2022. On the way to construct the estimated houses with traditional methods, there would be a tremendous amount of waste generated due to inefficient construction techniques, where the construction industry in India generates about 10-12 million tons of waste annually (Airveda, 2019). As a result, the government of India has set a technology sub-mission under the PMAY mission, which supports adopting new technology that would reduce the construction period, cost, waste, and makes construction more sustainable. As a result, 3D concrete printing technologies can be a promising solution under this technological sub-mission, which can open the way to mass customization in construction and can help achieve the construction of houses in the proposed time.

1.2 PROBLEM ANALYSIS

3D concrete printing is an automated construction technology that has the potential to transform the construction industry in terms of cost reduction, short construction periods, improve quality, and is more sustainable (Peng Wua, Jun Wang, & Xiangyu Wang, 2016). The potential advantages of 3D concrete

printing technology in housing are significant. Three-dimensional concrete printers offer design flexibility and enable the production of structures that are difficult to produce using conventional construction methods (Khoshnevis, 2004). Thus, as mentioned, 3D printing makes it possible to reduce the time required for construction, results in increased efficiency of management and logistics (Khoshnevis, 2003). Construction formwork costs can contribute for 35 to 54% of the total construction cost and can take 50% to 75% of the total construction time (Jha, 2012). Eliminating the expensive formwork by adopting 3D concrete printing processes not only has possibilities to reduce the costs and project time but also leads to a decrease in waste generation (Camacho et al., 2018). Benefits include improved not only efficiencies of the environment and financial resources (Tahmasebinia, Raghava Reddy, & Marroquin, 2018) but also the capacity to customize designs for aesthetic and structural applications to increase architectural freedom. Many recently completed projects by various companies have provided evidence that the 3D printing of houses can be realized on large scales with less construction period, and 3D printing technologies offer innovative solutions for affordable housing construction. With such benefits, its research interest in employing 3D concrete printing for construction has increased exponentially in the past few years around the globe (Tay, Yi Wei Daniel & Panda, 2017). However, many researchers have focused on developing different types of printers, design optimization, improving printing materials. Where they have been executed in many parts of Europe and the USA. Despite its maturity, not much research has been done on the adoption of technology on broad-scale application. The adoption of 3D concrete printing technology remains to be an essential topic since significant research being done to date and accepted in some parts of the world. 3D concrete printing is still not widely adopted in the Indian construction industry. Due to its limited knowledge of technology, legal barriers, and cost because of which companies have no proper planning in adopting 3D concrete printing technology, which needs to be addressed. Hence, this research will focus on identifying and assessing such adoption barriers and enablers in order to develop a roadmap to streamline the adoption of 3D concrete printing for affordable housing by contractors in India.

1.3 RESEARCH OBJECTIVE

The objective of this research is to develop a roadmap for the adoption of 3D concrete printing by contractors in India for building affordable houses. Roadmap development will be done through the analysis of barriers, risk, and enablers considering technology, economic and regulations dimensions for adopting 3D concrete printing for affordable housing in India. It is expected that this roadmap would result in the development of systematic strategies for the adoption of 3D printing technology in the construction of affordable houses.

1.3.1 RESEARCH SCOPE

This research aims at discovering the diverse factors affecting the adoption behavior of 3D concrete printing technology in the Indian construction industry for building affordable houses. Moreover, the research will be focused mainly on investigating the companies, as indicated in Figure 1. companies which are innovators, early adopters to understand associated barriers and enablers of the technology, from the perspective of the Indian construction industry. Thus, to create awareness among Indian contractors by providing a stepwise plan in the structure of roadmap indicating technology, regulations, and cost for implementing this 3D concrete printing technology for building affordable houses in the Indian industry.

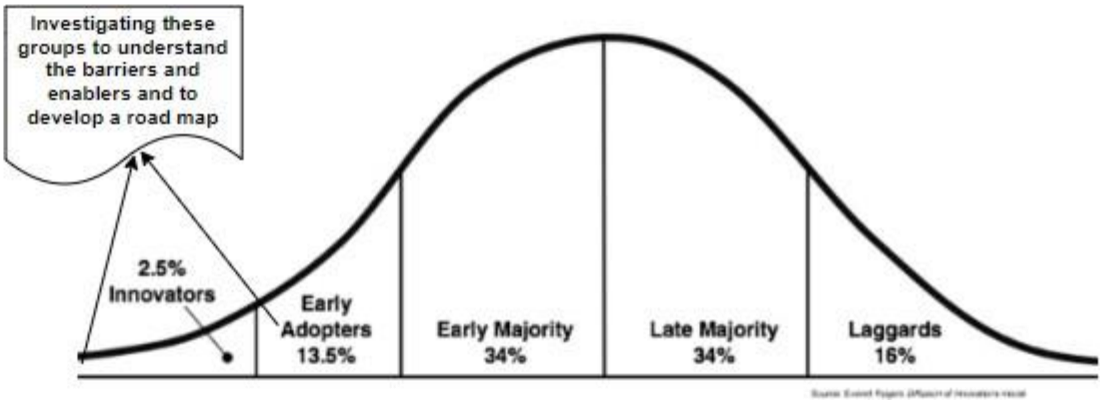

Figure 1: understanding the research scope with the help of the "Diffusion of innovation" curve developed by E.M. Roger

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1.4 RESEARCH QUESTIONS

The main question where this research tries to address is:

- What steps are required to streamline the adoption of 3D concrete printing technology for affordable housing by contractors in India?

Sub research questions:

1) How is 3D concrete printing technology being used at the moment by the construction industry?

2) What is the vision and value proposition for constructing affordable houses using 3D printing technology in the Indian construction industry?

3) What are the barriers and risks for companies in adopting such disruptive technologies in the Indian construction industry?

4) What are the enablers/opportunities in the Indian industry required to integrate 3D concrete printing technology and to construct affordable houses?

2. LITERATURE REVIEW

As stated in the previous chapter, the purpose of this research is to develop a roadmap to help the Indian construction industry become ready for the implementation of concrete 3D-printing technology in the construction of affordable houses. For that reason, it is vital to get an understanding of the technology. Therefore, the following chapter report on the review of relevant literature on 3D printing technology, its benefits, and its types in the construction industry. The literature on affordable housing includes global and Indian affordable housing gaps and the potential of 3D concrete printing technology for the housing shortage. The last chapters of the literature review consist of the current situation, barriers, and challenges of 3D concrete printing and adoption framework for analyzing factors influencing the adoption of 3D concrete printing technology in the Indian construction industry.

2.1 3D PRINTING TECHNOLOGY:

3D printing technology, also referred to as additive manufacturing and rapid prototyping, is described as a process by which 3D solid objects of any shape or geometry can be created from a digital file. The creation is achieved by laying down successive layers of a specific material until the entire object is created (Mukhaimar, Makhool, & Samara, 2014). Each of these layers represents a thinly sliced horizontal cross-section (similar to the output of an ordinary printer, this is why it is called printing) of the eventual object (Mukhaimar, Makhool, & Samara, 2014). Vigorous R&D efforts are now being made into large-scale building printing, reducing printing time for structural components, and increasing the print accuracy. The typical working of 3D concrete printing technology is shown in figure 2.

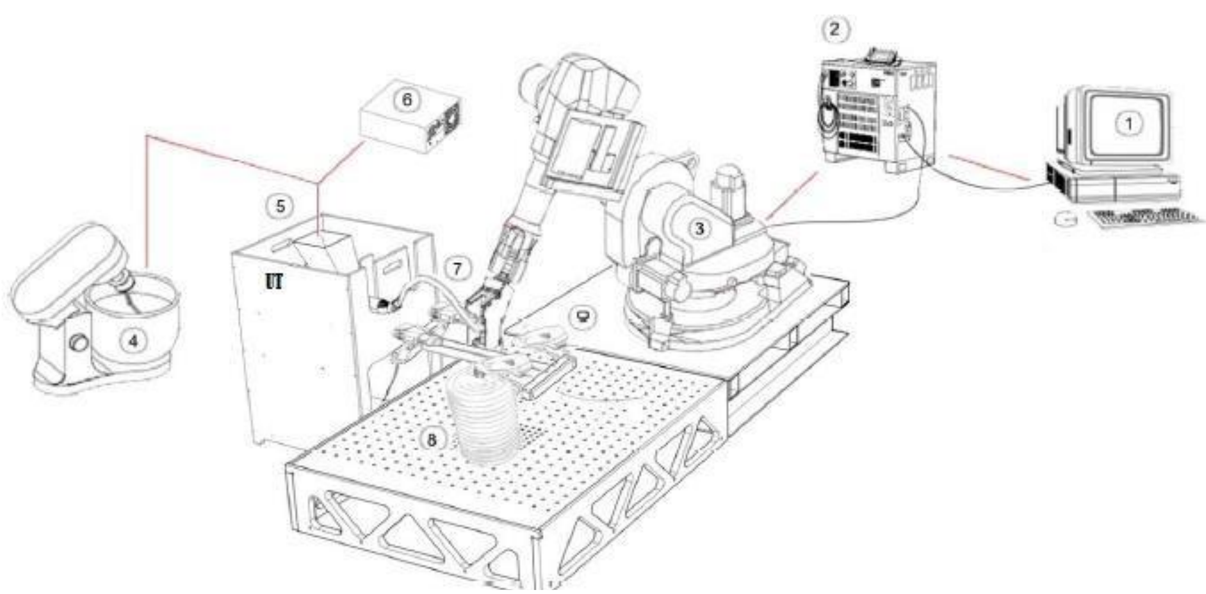


Figure 2: *Shows a diagram of the typical 3D-printing concrete system: (1) Computer for designing the toolpath and generating the G-code; (2) Robot controller for reading the generated code and controlling the robot, (3) Robot for moving the extruder nozzle along the generated toolpath; (4) Mixer for material preparation; (5) Develop pump; (6) Pump controller for running the code and controlling the pump speed; (7) Extruder; (8) Printed specimen; (9) Heat guns for heating the material during printing. source:(Flávio & Bilén, Sven. 2018)*

2.2 3D PRINTING TECHNOLOGY IN THE CONSTRUCTION INDUSTRY AND ITS BENEFITS

The construction industry has traditionally been very conservative, slow to innovate, and unsuccessful at boosting productivity (The Boston consulting group, 2018). However, looking at the global gross domestic product (GDP), while the construction industry represents a considerable part of the global GDP, its profit margins are somewhat limited. That is why many construction companies are continually trying to improve the efficiency of the entire process to reduce construction periods and reduce overriding costs. Since

construction companies are striving to improve efficiency, the limited implementation of 3D printing in the sector is rather surprising, as this technology is expected to increase the efficiency of processes. 3D printing technology in the construction industry is also called additive construction and is seen as a disruptive technology (Fiske, Edmunson, Fikes, Murphy Johnston, & Weite, 2018). Disruptive technology is one that replaces the current technology and revolutionizes the industry. Since Construction remains a mostly manual work, which makes it very expensive, moreover Construction is open to being disrupted by automation, and 3D printing is one technology that can support. The Boston group of consultants (BCG) stated in their report, "will 3D printing remount the construction" that 3D printing is a natural fit with the construction industry. This is because, as shown in Figure 3, challenges, demands, and required skills of the industry are an exact match to the advantages of 3D concrete printing technology.

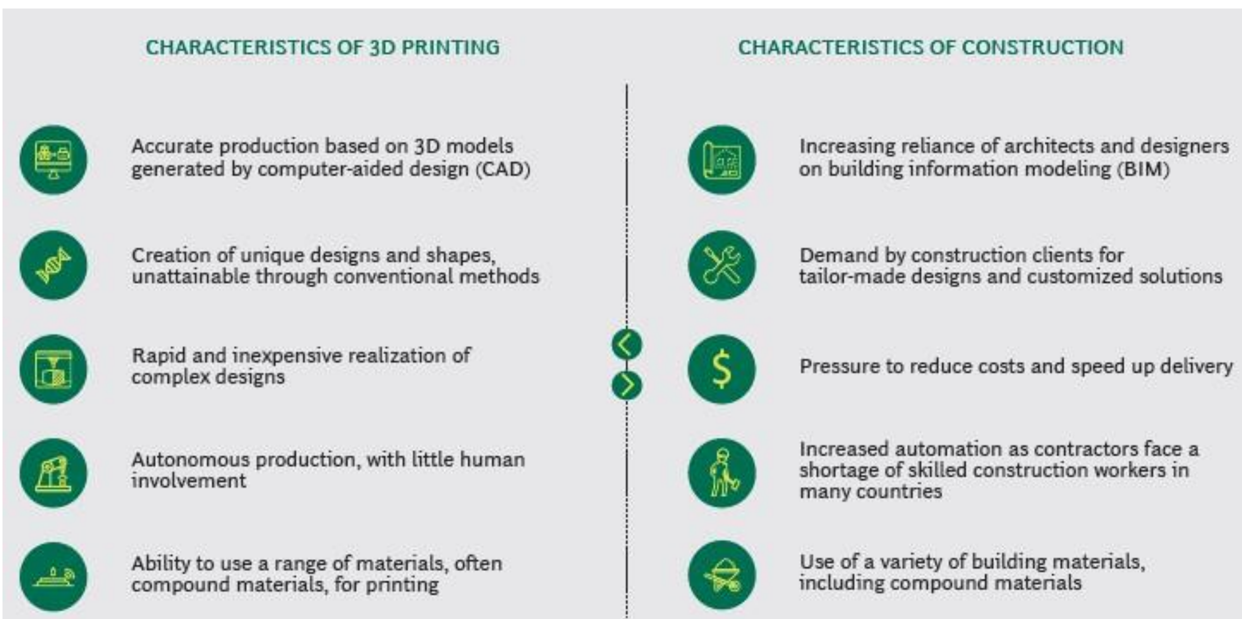


Figure 3:Showing 3D printing is a natural fit for construction.

Construction projects often require customized designs, and 3D concrete printing offers almost limitless freedom of design and the ability to fabricate complex shapes onsite or offsite, flexibly, and quicker construction. For construction companies, under increasing pressure from clients, taxpayers, and governments, the opportunity to autonomously print buildings or components 24/7 is bound to be a hugely welcomed prospect (The Boston consulting group, 2018). Against that background, the adoption of 3D printing by the construction industry has, sure enough, been accelerating. The reasons for this upswing can be summarized as technological advances, new entrants as 3D printing companies, strategic moves by well-established companies (The Boston consulting group, 2018). 3D printing debuted in the construction industry as a fast and accurate way to materialize architectural designs. Before long, the technology grew into producing genuine building components (Nematollahi, Behzad & Xia, Ming & Sanjayan, Jay. 2017). past few years, many 3D printings prototypes have developed and implemented in the construction industry, which shows that there is potential for this technology to be adopted in the construction industry for large projects.

3D concrete printing technologies open the way to mass customization in construction (Peng Wua, JunWang, & XiangyuWang. 2016) without compromising the design. Three-dimensional printers offer design flexibility and enable the production of structures that are difficult to produce using conventional construction methods (Khoshnevis B., 2004). 3D concrete printing technology makes it possible to reduce the time required to complete a building, which results in increased efficiency of management and logistics (Khoshnevis B., 2003). Moreover, construction formwork costs can contribute to 35 to 54% of the total construction cost and can take 50% to 75% of the total construction time (Jha, 2012). Eliminating the expensive formwork by adopting three-dimensional printing processes not only reduces the costs and project timeline but also leads to a decrease in waste material produced (Camacho et al., 2018). Besides the reduced costs of resources and formwork, 3D printing can also decrease transportation and installation costs (Muylle, 2019). Three-dimensional printing can help create a circular economy, which abandons the traditional 'take-make-dispose' economic model for a regenerative model. Creating a circular economy leads to many economic and environmental benefits (Peng Wua, JunWang, & XiangyuWang. (2016)). Besides all advantages mentioned above, 3D printing could also bring significant benefits in harsh environments by reducing exposure of on-site workers utilizing automating several construction tasks (Camacho et al., 2018). Harsh environments can be caused by human-made or natural disasters, for instance war zones or areas affected by an earthquake. However, these can also be aggressive environments such as deserts, the Poles, and chemically contaminated or highly polluted zones (Muylle, 2019). The construction of first response shelters (Howe et al., 2014) and the repair of broken infrastructure in natural disasters are potential applications that can be quickly manufactured, which can be of critical importance in these harsh environments (Muylle, 2019). For example, the INNOprint 3D printer, developed by the University of Nantes, can build a small emergency facility in less than 30 minutes, which is secured, isolated, and safe to live in (Muylle, 2019).

2.3 TYPES OF 3D PRINTING TECHNOLOGY AND PRINTERS DEVELOPED IN THE CONSTRUCTION INDUSTRY

It is essential for this research to address types of printers used in the construction industry, in order to reflect on the selection of the most appropriate and most economical printing technology for the future of constructing large-scale affordable houses. Different 3D printing technologies in the construction industry mainly differ in printing time, accuracy, cost, and printing materials. However, two distinct techniques can be identified, namely extrusion-based and powder-based techniques.

Extrusion based technique

The extrusion-based technique is analogous to the fused deposition modeling (FDM) method, which extrudes cementitious material from a nozzle mounted on a gantry crane or a 6-axes robotic arm to print a structure layer by layer. This technique has been aimed at on-site construction applications such as large-scale building components with complex geometries. It has excellent potential to make a significant and positive contribution to the construction industry (Nematollahi, Xia, & Sanjayan, 2017).

Powder-based technique

The powder-based technique is another typical AM process that creates fundamental structures with complex geometries by depositing binder liquid (or “ink”) selectively into to powder bed to bind powder where it impacts the bed. This technique is an off-site process designed for manufacturing precast components. The authors believe that the powder-based technique is highly suitable for small-scale building components such as panels, permanent formworks, and interior structures that can be assembled on-site.

As discussed above, the concrete 3D printer could be used in two ways in the construction industry. One option is to print elements in the factory, after which they will be transported to the construction sites and assembled. Another option is to set up the printer at the construction site where the structure will be printed in elements on the site and assembled, or directly print the structure on site. It should be noted that this practice is based on the printing of vertical elements by placing materials horizontally in layers on top of each other (Nadarajah, 2018). With these technology and application knowledge as background, two types of printers were developed and are currently in use in the Industry. The first type is a framed printer, also known as the gantry system, were printer would fit only in factories because it is challenging to transport and assemble it on site. The current barrier observed in this printer is that the frame of the printer must be larger than the structure itself. Increasing the size of the frame makes the printer expensive, challenging to transport, and assemble. Examples of the framed 3D printer are counter crafting developed at the university of southern California, Concrete printing developed by a team at Loughborough University in the United Kingdom, gantry system developed by TU Eindhoven in Netherlands and Vulcan printer developed by ICON in the USA. All of these printers use extrusion-based techniques. However, the D-shaped printer developed by Italian architect Enrico Dini uses a power-based technique.

The second type of printer is a non-framed concrete printer. This type of printers consists of a robotic printing arm that is usually mounted on wheels to relocate its position during printing. These printers can be easily transported and do not require a flat ground, unlike the framed printer. Examples of robotic arm printers currently used in industry are X1 & X1 core developed by Cazza robotic construction 3D printers, ApsiCor printer developed by ApsiCor, CyBe RC 3DP. These printers often use the extrusion technique (Saunders, 2017).

2.4 AFFORDABLE HOUSING

In many parts of the world, “affordability” is defined as housing costs that consume no more than 30 to 40 percent of household income (The McKinsey Global Institute, 2014). The idea of affordable housing recognizes the needs of households whose income is not sufficient to allow them to access appropriate housing in the market without assistance (O’Neill, 2008). In contrast, UN-HABITAT defines affordable housing as “housing which is adequate in quality, location and does not cost so much that it prohibits its occupants from meeting other basic living costs or threatens their enjoyment of basic human rights” (UNHABITAT, 2011).

2.4.1 GLOBAL AFFORDABLE HOUSING:

From London to Lagos, the increasing unaffordability of housing is a growing challenge to cities and nations. A rising share of residents, and not just the poor, pay a disproportionate share of income for housing or live in inadequate housing that is cut off from places of employment and access to health and educational services. The United Nations Universal Declaration of Human Rights explicitly includes decent housing as a fundamental human right. "Everyone has the right to a standard of living adequate for the health and wellbeing of himself and of his family, including food, clothing, housing, and medical care and

necessary social services…". The gap in decent, affordable housing extends virtually around the globe, as shown in Figure 4, challenging a significant social and economic toll on both developing and advanced economies, affecting both poor and middle-income citizens. Results are seen in the squalor of Brazil's favelas, the lack of sanitation in the slums of Mumbai, and the homelessness on the streets of Los Angeles. Mckensy has estimated that globally about 330 million urban households live in substandard housing or are financially stretched by housing costs that exceed 30 percent of income. Among more deprived citizens in high-cost cities, housing costs may consume as much as 70 percent of income.

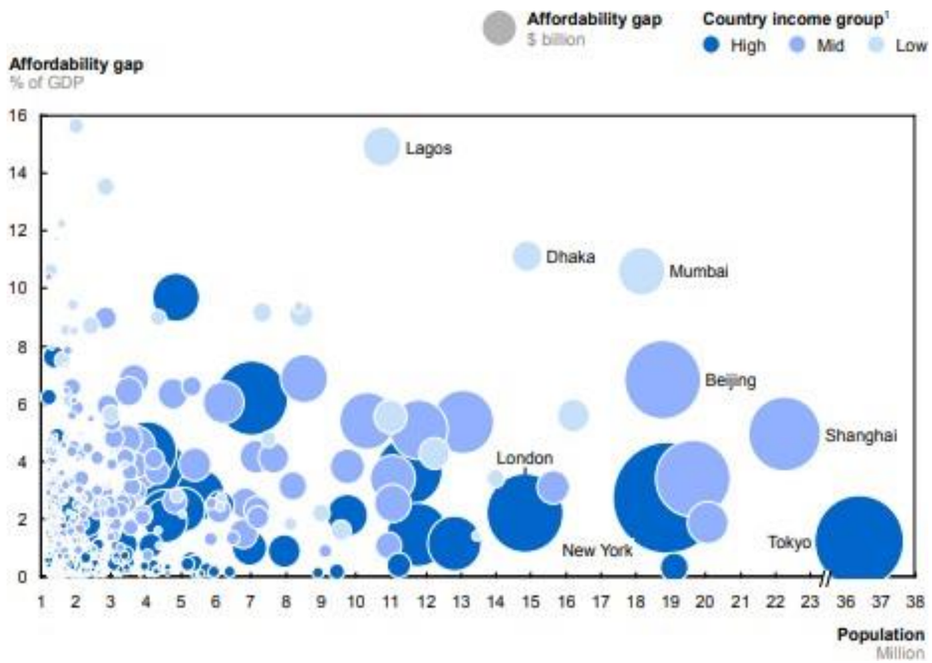
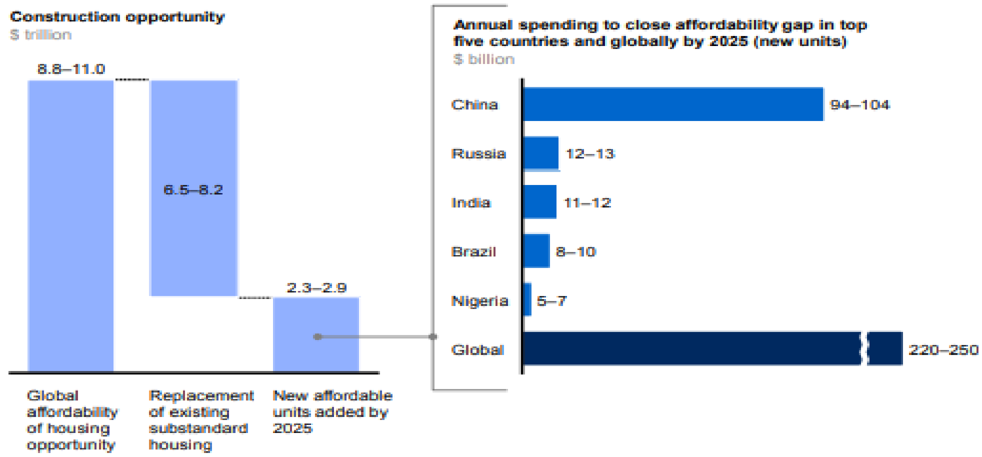


Figure 4:figure showing the global affordable housing gap. Source McKinsey Global Institute.

Affordable housing for all would require a $16 trillion capital outlay over decades. The prospect of trying to fill a gap of 440 million housing units (McKinsey Global Institute, 2014) that will be required by 2025 may seem daunting to policymakers. However, it could represent a massive opportunity for private contractors to fill this gap using advanced technology by adopting automated technology such as 3D concrete printing. The investment associated with building the houses needed to bridge this gap would be $9 trillion to $11 trillion for construction alone. With the cost of land, Mckinsey estimates the total could be as much as $16 trillion. Figure 5 below shows the annual spending to close the affordability gap in the top five countries and globally by 2050



1 Represents only additional low-income households entering cities by 2025 that will face affordability challenges.
NOTE: Numbers may not sum due to rounding.

Figure 5: Affordable housing gap and its associated construction cost across global. source: Mckinsey global

2.5 INDIAN AFFORDABLE HOUSING GAP AND NEED FOR ACCELERATING 3D PRINTING.

As seen in the Mckensy report, India is one of the top priorities in need of affordable housing. Rapid urbanization and the lack of planned affordable housing have led to a shortage of millions of urban homes in India. Though different countries have different definitions for affordable housing, it is mostly the same, i. e. affordable housing should address the housing needs of the lower- or middle-income households. Affordable housing becomes a critical issue, especially in India, where a majority of the population is not able to buy houses at the market price. Thus, Affordable housing from the Indian context refers to housing units that are affordable by that section of society whose income is below the median household income (ET, 2018). Different income households of the society have been identified by the Indian government that is eligible for affordable housing, as shown in Table 1.

Category	Household Annual Income	Maximum House Area	Govt Subsidy	NPV of Subsidy
Economically Weaker section (EWS)	<3 lacs rupees equivalent to (3.900 euros)	30 sqm	6.5% for loan up to 6 lacs	2,67 lacs (3.423 euros)
Lower Income Group (LIG)	3 - 6 lacs rupees equivalent to (3.900 - 7.700) euros	60 sqm	6.5% for loan up to 6 lacs	2,67 lacs (3.423 euros)
Medium Income Group 1 (MIG 1)	6 - 12 lacs rupee equivalent to (7.700 - 15.400) euros	160 sqm	4% for loan up to 9 lacs	2,35 lacs (3.012 euros)
Medium Income group 2 (MIG 2)	12 - 18 lacs rupees equivalent to (15.400 - 23.000) euros	200 sqm	3% for loan up to 12 lacs	2,35 lacs (3.012 euros)

Table 1:Criteria for eligibility for affordable housing in India, according to the mission "housing for all."

The government of India estimates that there are 26–37 million families in urban India that live in informal housing, with poor living conditions. These primarily belong to the economically weaker section (EWS) households and Low-income Group (LIG) households (Indian development review, 2019). Besides, more than 60 million homes in India are unfit for a decent living (National Buildings Organization (NBO), 2013). This means India needs 6.9 million houses each year, out of which 75% stands in the affordable sector, filling this gap with decent housing will entail a significant increase in energy consumption and related CO2 emissions, costs and would take a more extended period to meet the gap. The scheme was announced in 2015 by the Indian government I,e. Housing for all mission known as Pradhan Mantri Awas Yojana (PMAY), which aims to fill a total affordable housing shortage of 20 million by 2022, for the households with applicable subsidies shown in Table 1.

Under this mission "Housing for all," a technology sub-mission (TSM) has been set up to facilitate the adoption of modern, innovative, and green technologies for faster and quality construction of houses addressing the building of standard for the technology. Thus, constructing affordable housing by the use of 3D concrete printing can become a part of this submission, which can lend a hand for India to achieve the target that is aimed. Nevertheless, for that to happen, the ground reality has to be considered that 3D concrete printing is a relatively new technology for the Indian industry, according to the additive manufacturing society of India. The Indian market for 3D printing products & services is only 3.3% of the total Asia Pacific market (Anjum, Dongre, & Nihar Nanyam, 2017). However, there has been an increase in the demand for personal 3D printers, but high end and large-scale 3D printing technology is still missing in India (ET technology, 2017). Hence, there is a requirement of generating awareness about the application of 3D printing in the construction industry as well in the educational institutes, and emerging professionals is essential, as they would be the future of the Indian construction industry.

The motive behind choosing an Indian context can be coupled with the initiative taken by the Indian government to adopt new technologies and from the literature. Where researchers David Weinstein and Peter Nawara, in their research, "Determining the applicability of 3D concrete construction of low-income houses in select Countries," found the top 10 countries that were suitable for adopting 3D concrete printing. By conducting quantitative research using various parameters such as wealth: GDP at purchasing power parity per capita, size: number of housing units existing, likelihood to consume forecasted single-person housing need, actual consumption per capita (Weinstein & Nawara, 2015). The countries shown in Figure 6 are considered to be suitable for implementing the 3D concrete printing technique as a construction method for affordable housing (Weinstein & Nawara, 2015). Therefore, with this outcome, we

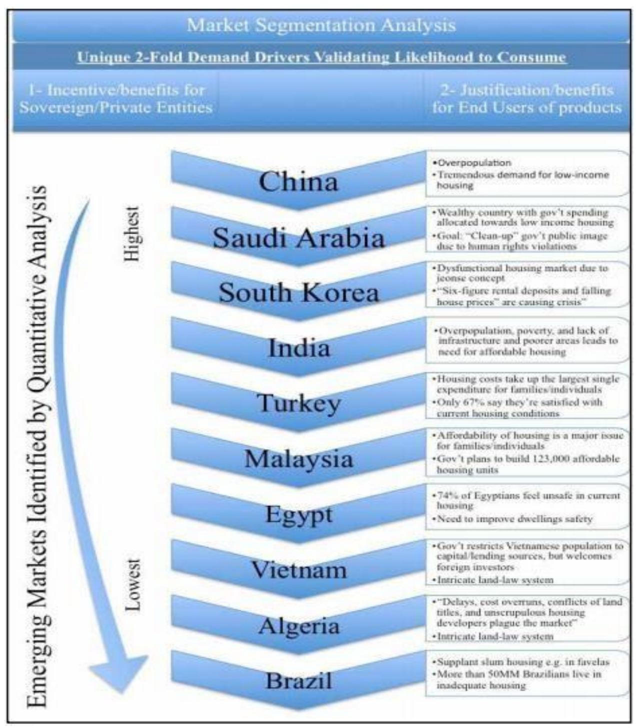


Figure 6:TOP 10 countries most suitable for implementing application of 3D concrete printing for affordable housing

can conclude that the context on to the adoption of 3D concrete printing in the Indian construction industry constructs a good judgment.

Summarizing the above affordable problems, the affordable housing problems of the 21st century that include continuous urbanization, overpopulation, pollution, energy deficiency, land shortage, and lack of affordable housing cannot be solved by applying housing solutions of the 20th century. The paradigm shift initiated by the disruptive new technological development of the fourth industrial revolution is offering substitution to the conventional understanding of housing design, its production processes and radically change the way we live and work. This research examines and describes new prospects, opportunities, and limits of housing by the use of innovative advanced 3D printing technologies. That introduce new possibilities to the process of housing design, fabrication, and construction, which 3D printed technology could hold the key to producing affordable housing quickly without sacrificing design. These new possibilities in housing design include research in form, function, structure, and materials. They have a profound influence on both architectural research design, its production process, and significantly reduce overall investments, time and resources, materials, and labor use, decrease pollution and energy use. Nevertheless, 3D concrete printing technology has yet to reach the development required to be implemented at the scale necessary to address this problem. There is substantial evidence that within the foreseeable future, it will become a viable solution and even fundamentally change the traditional construction method.

Correspondingly, 3D concrete printing of buildings can bring significant advantages to the Indian construction industry mitigating the problems mentioned above. Thus, with an increase in population in developing countries like India, traditional methods of construction will not meet housing demands, especially in areas where a higher construction standard is required for safety precautions. 3D printing seeks to address housing problems and can provide people with a quick construction period and dignified housing (Weinstein & Nawara, 2015).

2.6 CHALLENGES IN USING 3D CONCRETE PRINTING.

As an innovative technology, 3D concrete printing offers a significant opportunity for the construction industry. Such as, increased flexibility and reduced operational costs. However, it is essential to analyze and understand the barriers and challenges to augment the success potential of implementing 3D concrete printing technology in the construction industry. Many studies show that the construction industry has failed to adopt innovations to improve its performance as in other industries (World Economic Forum, 2016). The lack of stakeholder's involvement, high initial innovation costs, lack of risk funding, inherent conservative behavior of organizations, regulatory barrier, and initial non-profitability of innovations are some examples of barriers leading to fails in the adoption of 3D concrete printing innovation.

Naturally, 3D printing technologies do not only bring advantages to the construction industry, but there are also still many challenges and restrictions that limit the widespread application. The construction sector, with its traditional methods, is quite resilient to change (Paoletti, 2017). This can slow down the adoption process for disruptive, innovative technologies like 3D concrete printing. Practitioners think that high rise construction applicability of 3D printing technology cannot be achieved at the moment, In the early studies, it was thought that 3D printing technologies might not be suitable to create large-scale models or structures (Gibson et al. 2002). These claims were doubled because of using the small size of 3D printers in the initial phase of technology.

On the other hand, with the development of new 3D printers in recent years, many large-scale models or structures have been created using these large-scale 3D printers (Wu et al. 2016), which shows that high rise apartments can be constructed in the countries which have land scarcity. In addition to the size of the printers, the materials play a significant role in 3D printing. In the construction industry, almost all of the 3D printing production work is focused on concrete. This has led to minimal availability of the currently owned material palette. The durability and mechanical characteristics of the printed products using the latest printing materials must be high performance for the use of 3D technology in large scale models and structures. However, due to the difficulty of having high-strength printing materials, it is thought that 3D printing cannot be used in large scale models and structures. However, it has been proven that it may be as effective as various materials modified and have attained high-strength printing materials but are way too expensive at the moment (Tosun, yeşim & Şahin, Remzi, 2019). Examining the current state of the 3D printing materials, it is seen that there is still not enough focus on material properties. The studies on concrete are mainly related to the initial strength and long-term strength, the load-bearing capacity parameter. Although the materials used for 3D printing technology are examined in terms of their load resistance capacity, they are rarely examined for their fire resistance, durability, and thermal properties (Ngo, Tuan & Kashani, Alireza & Imbalzano, Gabriele & Nguyen, Kate & Hui, David, 2018). When physical performance is checked in detail, some mechanical and physical properties may be poorly observed. Moreover, the life cycle sustainable analysis performance of 3D concrete printed projects remains uncertain as the 3D concrete printing technology is still in its infancy (Masera et al., 2017). Nevertheless, there is no standard been developed by any standards bureau in the world for easy integration of 3D concrete printing in construction projects, which remains to be a significant barrier for 3D concrete printing technology.

Internal factors	
Strengths (S) ❑ Reducing construction time ❑ Increased precision ❑ Reduces construction waste ❑ Minimises transportation cost ❑ Allows for complex geometries realisation. ❑ Better control of the construction process	Weaknesses (W) ❑ High capital cost & expertise needed ❑ Technical problems; applying reinforcement, control of print path, height and speed as well as the rate of extrusion. ❑ Design parameters; apparatus design and operating system ❑ Material content: flowability, buildability, extrudability, stiffness and strength.
External factors	
Opportunities (O) ❑ Applying BIM integrated technologies ❑ Integrating latest scientific findings with industrial practices ❑ Competitive advantage of 3DP and the real estate market acceptance and future development including clients and customers	Threats (T) ❑ Socioeconomic consideration: reducing job opportunities ❑ The need for special building codes that suit the use of the technology ❑ Less incentives and awareness

Figure 7:SWOT analysis of using 3d concrete printing technology (Omar Geneidy, Walaa S.E. Ismaeel,2019).

To clinch, understanding the benefits and challenges in 3D concrete printing, a SWOT analysis was carried through the survey method of data collecting by Omar Geneidy and Walaa S.E. Ismaeel,2019. SWOT analysis is shown in, which briefs the external and internal factors that affect the widespread application of this technology in the local context of Egypt, these factors, which more or less can be considered in the local context of any country (Omar Geneidy, Walaa S.E. Ismaeel,2019). The factors are attributed to the strengths and weaknesses of the technology itself. At the same time, the latter represent external factors that may be considered as opportunities or threats of applying this technology in the local construction market. These internal factors and external factors will be further incorporated in drafting parameters under TEC dimensions, which will be used in the data collection phase.

2.7 ADOPTION FRAMEWORK

A wide range of adoption models has been developed to understand better the different dimensions that influence the acceptance of technologies (Muylle, 2019). The technology-organization-environment (TOE) framework, which was developed by Tornatzky and Fleischer (1990), has been widely utilized to explain how to adopt technological innovation from the perspective of an organization (Yeh, C. C., & Chen, Y. F. 2018). TOE framework was selected as the finest model for this research, for the reason that it is more extensive than other theories for instance Diffusion of innovation (DOI) theory. This framework identifies factors that directly influence an organization's implementation of technological innovations: technological context, organizational context, and environmental context. Although previous studies have identified these as important factors that can promote the adoption of technological innovation, these factors do not play significant roles concerning 3D printing (Yeh, C. C., & Chen, Y. F. 2018). The framework further needs to incorporate cost dimensions as one of the critical factors to the widespread adoption of 3D concrete printing from the perspective of an organization. Thus, the TOE framework was extended to e TOEC framework in the paper of Yeh & Chen (2018) regarding the adoption of 3D printing in the manufacturing industry. Where it was revealed that the different costs played an essential role in the organizational adoption decision, which is the utmost crucial dimension for Indian contractors. However, the organizational dimension, which can be categorized into the technological readiness, size of an organization, the structure of the organization, and support from the top management does not have considerable influence on developing the roadmap. Since the roadmap will be developed for adopting technology for the organizations, hence the organization dimension can be given a priority once the roadmap is developed. Therefore, the organizational dimension will be overlooked from the framework to improve the quality of research in a constrained time. Accordingly, to develop a roadmap, these dimensions will be used as the basis to analyze the barriers and opportunities in order to stepwise streamlining the adoption of 3D concrete printing technology for affordable housing by contractors in India.

2.7.1 Technological dimension

It is emphasized by Mellor et al. (2014) that the technology benefits derived from a potential additive manufacturing implementation need to be linked to the company's business strategy, in order to gain competitive advantage. However, it is equally essential that the company understands the trade-offs or potential sacrifices. Even though the range of available materials and technology is continually growing, it is still limited. Furthermore, there is still a lack of technical standards, which is considered as a barrier to the implementation of 3D concrete printing technology across industries (Muylle, 2019). The related technologies that are available in the marketplace for potential adoption have to be taken into account as well because they demonstrate how organizations can expand (Oliveira et al., 2014) their capability to use 3D concrete printing technology mainly to build affordable houses. Five innovation attributes that are associated with the technological context are derived from DOI (diffusion of innovation) theory (Ramdani, Chevers, & Williams, 2013). Namely, relative advantage, compatibility, complexity, observability, and trialability.

2.7.2 Environment dimension

The environmental dimension focuses on the external factors that influence the adoption process of innovations in an organization, like the industry with its competitors, and government incentives and regulations. As a result, these market-related factors affect the organization through external channels. These factors are crucial to inherit an alignment of business, manufacturing, and R&D strategies. (Mellor et al., 2014). The industry structure and market in which the firm operates have an essential impact on the adoption behavior of the organization, with severe competition leading to the stimulation of technology adoption (Mansfield, 1968). The industry life cycle also influences adoption behavior; organizations that are part of fast-growing industries incline to innovate more quickly (Tornatzky & Fleischer, 1990). Environmental features deliver their influence through a correlation with technological innovation by the fact that they rely on each other. The regulatory environment imposed by the government can either encourage or hamper innovation adoption, for example by providing tax advantages or enforcing new constraints respectively and implementing technical standards for new construction methods (Yeh, C. C., & Chen, Y. F. 2018). The government can increase housing supply by releasing under-utilized land for residential development by aiming to enable efficient land allocation for housing in urban areas with existing infrastructure, without the need to develop country parks or reclaim the land. Government policies would help lower construction costs and shortening the overall project life cycle of housing development will help to speed up the supply of new residential units to the market as well as decrease the overall cost of housing. Strict safety and testing conditions, for example, in the construction industry, can hamper the adoption process (Baker, 2011).

2.7.3 Cost dimensions

Cost is correspondingly another crucial aspect for understanding the success of 3D concrete printing for constructing houses. Its cost is calculated based on different factors, including the fixed cost of printing resources, usage cost, and the cost for technical maintenance of the current infrastructure. Besides, 3D printing implementation is associated with various forms of related investment, including investment into hardware, software, or system integration (Yeh, C. C., & Chen, Y. F. 2018). Based on the diverse and extensive features of cost, organizations may realize a sizable amount of expenses related to this type of project. Moreover, the cost of constructing the house using this technology plays an essential role in the phase of adoption by local contractors. Therefore, this research takes into consideration specific types of costs for 3D printing, like material cost, machine cost, labor cost, and maintenance cost. From the literature review and interviews with industry experts, thereby gathering instrumental dimensions and criteria for exploring the various factors and effects of 3D printing implementation. Based on the TOE framework, the cost dimension into account is taken into consideration, which plays an essential factor for Indian contractors.

3 Research Methodology

This chapter describes the methodology that will be applied in this research, which is summarized in Figure 8. Detailed elaboration of the methodology is provided in Sections 3.1 to 3.5, respectively.

3.1 PHASE 1: LITERATURE STUDY

The first phase of this research consists of a literature study. The motivation behind the literature review is to (1) acquire the knowledge on 3D concrete printing technology used for residential building projects in the construction industry in the global and Indian markets. The purpose of reviewing 3D concrete printing technology is to capture the state-of-the-art in the area of 3D concrete printing and to identify the current barriers, risks, and challenges in adopting 3D concrete printing. Moreover, (2) capture the knowledge of global affordable housing and Indian affordable housing. Besides, reviewing the literature on affordable housing is to analyze the current problem of affordable housing in India and worldwide and its projection in the future. Moreover, the literature on 3D concrete printing as a supply solution to fill the housing crisis will be reviewed for gathering the knowledge on how 3D printing can facilitate the affordable housing crisis currently will be documented. Finally, once there is explicit background knowledge on these two subjects, a framework for the interview-based data collection can be created.

Key phrases that are used are as follows: 'Adoption of innovation in the construction industry,' '3D concrete printing', 'Innovation in the construction industry,' '3D printing in the construction industry' 'innovation in Affordable housing,' and '3D concrete printing for affordable housing.

3.2 PHASE 2: DATA COLLECTION

The purpose of the data collection is to obtain qualitative data with in-depth interviews on how the companies recognize barriers and opportunities concerning Indian context on using 3D concrete printing for affordable housing. Moreover, how they vision technology would be adopted in the future to analyze the vision and to create a roadmap. Thus, this phase would result in collecting and recording the data according to the dimensions concerning adoption models TOE (Technological, Organizational, Environmental) framework. The framework which was developed by Tornatzky and Fleischer (1990) and has been widely utilized to explain how to adopt technological innovation from the perspective of an organization (Yeh, C. C., & Chen, Y. F. 2018). As discussed in section 2.7 adoption Framework the organization dimension was overlooked and thus TEC framework was selected as the most elegant model for this research.

3.2.1 Interviews

A set of interviews will be held with the people from a different organization, and mainly the organization will be chosen with expertise on 3D concrete printing, the organization for example companies which are innovators and early adopters of 3D concrete printing, technical universities, and government organization. Furthermore, Interview questionnaires will be divided into three parts, namely technology, environment, and cost dimensions. Moreover, for each part, the potential stakeholders will be identified with a suitable background for finding out the barriers and enablers that influence the adoption behavior of 3D printing in the Indian construction industry. The question will be based on TEC (Technology, Environment, and Cost) dimension. Moreover, the question in each part will be divided into two sub-parts I, e. to understand the technology at the current state and how the technology will be at and future state concerning its potential of constructing affordable houses. Moreover, due to the qualitative approach, the focus of the data collection will depend on time constraints on how many interviews with deep character will be carried out. Every interview will be recorded in order to proceed to the next stage, which is data analysis. The questionnaires will be derived mainly from a literature review concerning 3D concrete printing and brainstorming, which further will be verified by supervisors.

Thus, according to above research strategy, Before the interviews started, literature research was performed and finished. Based on this, the interview questions were composed, and the interviews were conducted. The experts of 3D concrete printing in India for the interviews were selected based on reviewing the news articles, published technical paper, and by indication of the interviewees to other experts. Firstly, active research on 3D concrete printing in the Indian universities was looked at, by that means the IIT professor (Dr. Manu Santhanam) was interviewed. Similarly, the different companies involved in 3D concrete printing were traced and then were invited for an interview. Likewise, the government authorities from the Ministry of housing and construction developers were invited to give a holistic view of the research. Table 2 below shows the list of interviewees and their designation.

SL no.	**Organization**
	Educational institutes
1	Associate professor at Indian Institute of Technology, Madras
2	Assistant Professor of Additive Manufacturing & Design, IIT Guwahati {validation}
	3D concrete printing companies
3	CEO at OZAZ global.
4	CEO at Tvasta
	Government Organizations
5	Director, Ministry of housing and urban affairs
6	Executive Director, Building Material and Technology Promotion Council (BMTPC).
	Construction companies
7	Head - R&D, Tata Housing Development Company Ltd
8	General manager, Operational and technologies at Sapoorji pallonji
9	General Manager at Prestige Group of constructions {validation}
10	Deputy General Manager at Larsen & Toubro {validation}
	Researchers
11	Ph.D. Researcher at Virginia Tech, Virginia
12	Researcher at Central building research institute, Roorkee (CBRI)

Table 2:Showing the list of interviewed experts

3.3 PHASE 3: DATA ANALYSIS

In this phase, the grounded theory method will be used to analyze the data collected from the interviews. This method can support the creation of a theory that can later be used to explain a phenomenon and act as the basis for development of the roadmap. The grounded theory method provides the researcher with the ability to analyze specific cases and use the conclusion from these cases in a comprehensive manner. To analyze data using grounded theory, several steps need to be performed (Vidarsson, 2015). First of all, the investigators should write short memos when getting acquainted with data collected from literature studies. The collected data should also be coded, using a set of variables such as name, keywords. The codes should then be categorized by finding links between different codes and group these codes together.

When the codes have been categorized, the researchers should reduce the number of categories and reduce the number of codes that could not be grouped. The reason for this is that a vast number of categories would hamper the research. In order to do this, the investigators should group the categories with secure connections into one broader category, and those without a secure connection should be grouped into a category with a broader scope. The described process should be looked upon as a continuous cycle where the researchers analyze and collect data (Vidarsson, 2015). The stepwise coding process is represented in the and is further explained in section 4.3.1.

3.3.1 Coding

Mainly, the Grounded Theory generates the building blocks of the analysis. Theoretical analysis will assemble these building blocks into a functioning building. Hence, coding shapes the analytic frame from which the analysis will be built. Coding is the critical link between collecting data and developing an emergent theory to explain these data. Through coding can be defined what is happening in the data, and it is possible to grapple what it means (Charmaz K., 2006).

Open coding:

Open coding is the phase in which data are broken down and classified into smaller groups (Strauss & Corbin, 1998). In the data analysis phase, the interview transcripts will be analyzed line by line from collected data through semi-structured interviews. Which further will be broken down into different code or categories, for example with the regulation, compatibility, advantages, disadvantages, printer cost and material cost industry. Further, a deductive coding approach will be used where it starts with an initial list of codes, where the researcher can compose this list based upon the conceptual framework used during the data collection, which in this research is the TEC framework.

Axial coding:

The process of relating categories to their subcategories, termed 'axial' because coding occurs around the axis of a category, linking categories at the level of properties and dimensions" (Strauss & Corbin, 1998). The open coding phase leads to a highly elaborate set of codes with many labels occurring twice. The axial coding phase consists of two fundamental stages. First, it is essential to eliminate redundant codes. After that, separate codes have to be unified and related to each other to link the main categories and subcategories.

Selective coding:

The last step used selective coding to integrate and refine the categories into a theory, which accounts for the phenomenon being investigated (Strauss & Corbin, 1998). validates the statements of relationships among concepts and fills in any categories in need of further refinement. After sorting the data, it will be further used as input for developing the roadmap.

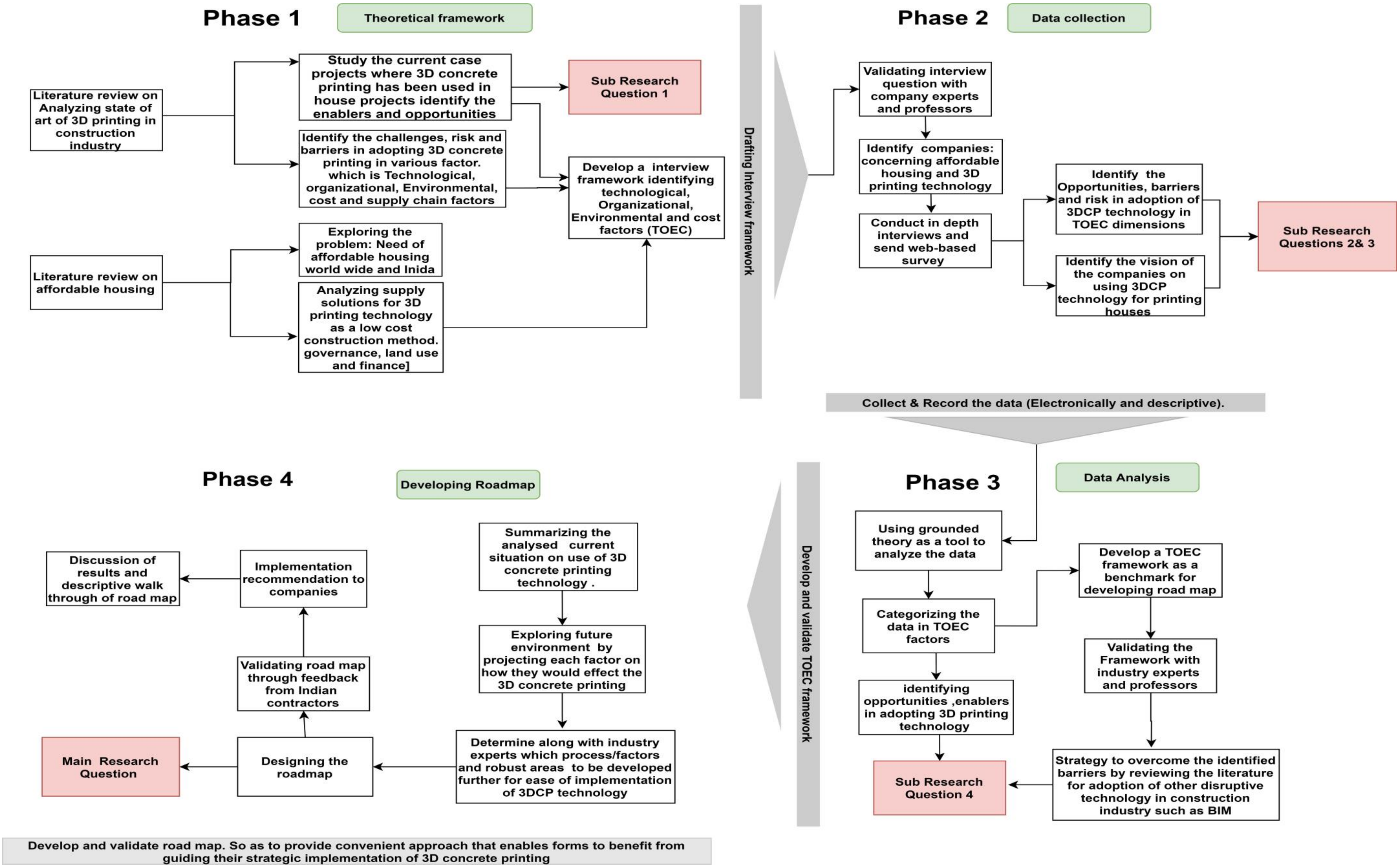


Figure 8:Illustration of research methodology

3.4 PHASE 4: RESULTS, DEVELOPING ROADMAP & VALIDATION

After analyzing the data in various dimensions, it will be used as the basis to project the future use of 3D concrete printing in the Indian context to build affordable housing. Subsequently, once a vision is established, the roadmap development phase begins, drawing on analysis and expert judgment to define the activities, priorities, and timelines required to reach the desired vision. Accordingly, the roadmap will be designed to bridge the gap of the current state and vision.

The roadmap development includes three primary layers, which are technology, product, and market that were proposed by Vishnevskiy et al. which according to R. Siebelink, review it as a business roadmap, which is defined as a visual representation of how the markets, products, and technologies of a firm evolve. This roadmap will be a time-based graph consists of separate layers for technology, product, and market that provides how elements in these layers are linked to each other (R. Siebelink, 2013). A business roadmap as a such provides a way to develop, organize and communicate the targets that must be satisfied by specific time frames with technologies and products that need to be developed to meet the need for adoption of 3D concrete printing in a contractors firm.

"Business road mapping is a powerful technique for supporting technology management and planning in the firm. The generic roadmap is a time-based chart, comprising several layers that typically include both commercial and technological perspectives. The roadmap enables the evolution of markets, products, and technologies to be explored, together with the linkages between the various aspects" (Phaal, Farrukh, Mitchell, et al., 2003, p. 52).

3.4.1 Application of roadmap

There are wide range applications of the roadmap, recently roadmaps have become an application instrument used by the private and public sectors, for instance, governments, companies, and public bodies involved in technology and innovation. Roadmaps aim to identify promising technology and the impact assessment of the decisions taken. Technology and the market dimension need to be integrated into one roadmap to shift the focus from developing or adopting technology to the application of technologies. Accordingly, there remains a need for improved and sophisticated methodologies to make concrete innovation strategies based on road mapping. Road-mapping strategies include a comprehensive reflection of technological and market prospects, taking into account expert knowledge from different fields (Vishnevskiy et al., 2015a; Khripunova et al., 2014). Thus, this research considers the vast knowledge from industry, government, and education institutes experts to collect the data on 3D concrete printing technology pertaining to the Indian industry and its market environment.

Moreover, the roadmap is a very flexible approach in both aims and graphical forms (Phaal et al., 2004; Probert & Radnor, 2003). Besides, roadmaps can be used as both retrospective means to discover past technologies, products, and linkages that were successful, and as prospective means to plan for the future. Basically, Four types of primary roadmap types can be identified, science and technology roadmaps that help to understand the future by specifying trends (R. Siebelink, 2013); industry roadmaps that describe the future paths of progress in an industry by defining the industrial context and competitive landscape in combination with technology progression; product-technology roadmaps for combining product evolution with trends and the firm's strategic objectives; and the product roadmap to communicate product evolution to stakeholders. As this research focuses on the development of a business roadmap for adopting 3D concrete printing by contractors in India, a product-technology roadmap is appropriate. Groeneveld (2007) and Phaal and Muller (2009) add that after such a product-technology roadmap for strategic purposes is developed, it is possible to develop a family of product-technology roadmaps within a firm for specific operational business.

When developing a roadmap to be incorporating in a firm, a common distinction is made between product or process innovations. Product innovation is a new output of an organization that is introduced to increase the benefit of an end-user. In contrast, process innovation is related to the way a product is made. The three-layered roadmap to be developed in this research will focus on the application of process and product innovation. The product, which is a house, will be built in an innovative way using a process of 3D concrete printing for an affordable housing market.

3.4.2 Validation of the roadmap

The created roadmap will be furthermore validated by collecting the feedback from Indian contractors to assess if the roadmap could guide them in the implementation of the technology in their organizations. Validation of the roadmap will be carried out based on requirements that were generated from scientific literature and guidance from supervisors. Seven major validating requirements were formulated, which are:

- Completeness: The roadmap includes the relevant technology, regulations, and cost dimension strategies to cope with the uncertainty in the internal and external environment for the adoption of 3DCP.
- Areas of future actions: The roadmap process should give direction to future innovations by defining multiple strategically essential areas and actions to adopt 3D concrete printing into organizations.
- Easiness to understand: The roadmap drafted should be suitable for communication, and thus easy to understand, for this simplicity is very important aspect of roadmap.
- Usability: The roadmap process is simple to execute with understandable activities in each layer. Moreover, the business roadmap must cope with the uncertainty in the external environment by being both robust and flexible.
- Adaptability: The roadmap process is practically applicable and is flexible to add new factors/dimensions to keep the necessary time and effort limited.
- Realizability: The roadmap timeline and activities that will be drafted can be implemented realistically.
- Suitability: The structure of the roadmap and the adoption actions mentioned enhances the implementation of 3D concrete printing by an Indian contractor.

4. RESULTS

For converting the raw data from the in-depth interviews, a coding table was used. The useful information gathered from the interviews was copied into the first column of the table, and overlapping points discussed by different interviews were put in the same row. Then this data was broken in the second table using open coding. In the last column of the table, the fractured data was re-build, using axial coding, establishing relationships between categories and their subcategories. The information per data source was kept separate, so that the data could be traced back to the source in a later stage, for an overview of the coding tables see supplement 2. Correspondingly, four separate coding tables were established for Current state of the art, obstructions, enablers, and future opportunities making perceptive easier. Hence, in total, four tables were established. An example of the coding tables is displayed in Table 3, which shows an example of how the raw data was converted to axial codes.

Raw data	Open coding	Axial coding
Time is saved since no formwork is used. Complex preassembling of the framework is eliminated. Additionally, labor reduction would be an advantage as there is not much available of quality labor, 3D printing makes the quality of construction better and safer. (Dr. Manu, IIT madras). Labors: upon setting up equipment, only 2 to 3 personals are required to carry out the whole operations. The reason behind researching this technology: since the government-funded research institute, we had to align the research with the government interest. With the PMAY, there needed scalability of houses, and making process more automation, and safer was the main motivation driver to research 3D concrete printing. Timesaving will be the main advantage for the scalability of housing given the gap. (Surya M, Central Building Research Institute (CBRI)) Time reduction will be the main advantage of adopting 3D concrete printing. In the long run, there is also very much possibility of bringing the entire cost down using 3D printing technology. (Aditya CEO tvasta)	Technology benefits	Timesaving on constructing the houses Reduction in unskilled labor Safety on construction sites Increasing the quality of construction

Table 3:Example of the coding table: showing breaking down of raw Enablers interview data to axial codes.

Later the data from the axial coding was attached to the technology, environment, and cost framework, as explained in section 2.7 Adoption Framework. For instance, timesaving on constructing houses, reduction in unskilled labor, and safety on construction sites were translated into selective code "technology." Later, the Triangulation method was used to check and establish the validity of a study by analyzing a research question from multiple perspectives. The Triangulation was used to find the similarities between the enablers and barriers within a category. So, within each column, enablers derived from various interviews and enablers derived from the literature research were compared to each other. Similar codes were recoded and displayed as one code. Besides, the same procedure was repeated for the barriers, which are shown in table 3 and table 4.

4.1 ENABLERS:

From the raw data, 27 enabler codes were found, which are shown in Table 4 that make it possible to overcome the obstructions. These enablers indicate the benefits (added value) of the 3D concrete printing technology, making the technique feasible and or advantageous to use.

Consolidated list of enablers		
Category	Codes	Enablers (E)
Technology (TE)	TE-E1	Faster construction, I, e Time saving on construction of houses
	TE-E2	Reduction in unskilled labour force
	TE-E3	Safety on construction sites, Reduction in site injuries and fatalities.
	TE-E4	Increase in the quality of constructing the houses
	TE-E5	Increased sustainability of houses: Sustainable mix can be used to construct the large number of houses.
	TE-E6	Mass customization in affordable houses
	TE-E7	Improved performance in housing delivery
	TE-E8	Reduction in required storage areas, equipment storage space on site as well as in factories is significantly reduced
	TE-E9	Reduction in material wastage. As robot placed the material wherever necessary without error, wastage is eliminated
	TE-E10	the process is more efficient than the traditional construction
	TE-E11	Robotic arm: Ease of transportation to the construction site
	TE-E12	Gantry systems: Printing complex modules and then assembling the module houses on site
	TE-E13	Considerably durable material. Since there is low water content and more cement content and additive mix. Thus, making houses more durable.
	TE-E14	Technology will become more advantageous for constructing the houses in earthquake prone areas.
	TE-E15	No water curing is required for the structure. Making the construction sites more organised and saving the water
	TE-E16	Constructing in extreme weather temperatures, quick home in disastrous areas.
	TE-E17	3D concrete Material is structurally stronger than the traditional concrete.

Environment (EN)	EN-E1	Market trends: In 10 years the market will see many 3D printed homes in India. As many large players are aware of 3DCP and started looking to adopt the technology.
	EN-E2	India has large affordable opportunity; thus, Government is promoting through support of new technology usage in affordable housing sector.
	EN-E3	Ministry of housing responsible for affordable housing Built an ecosystem with BMPTCL to bridge the gap between research and development and large-scale application of new building material technologies Where the council will evaluate the technology and will award it PAC certificate which is like the pre standard with this the any local or foreign company can start doing business in affordable sector using new technology.
	EN-E4	Government has taken initiative to support through financially to research on 3D concrete printing in India at IIT
	EN-E5	Supporting environment: Research Universities are open for collaboration with companies
	EN-E6	3DCP can decrease the impact on the environment by lowering the carbon emissions by using sustainable.
Cost (CO)	CO-E1	Reduction in labour costs
	CO-E2	Reduction in material costs, Lower concrete cost by using the waste construction materials in mix design
	CO-E3	Reduction in transportation costs
	CO-E4	Houses build are 25% cheaper than the traditional construction. (According to one organisation estimate)

Table 4:Consolidated list of enablers

4.2 BARRIERS:

Concerning the obstructions, 28 selective codes were found which are shown highlights the analyses of barriers concerning adoption of 3D concrete printing in Indian industry.

Consolidated list of barriers		
Categories	Codes	Barriers (BR)
	TE-BR1	Method of manual installation of reinforcement into 3D printed cavities cannot be used in every unique and complex design.
	TE-BR2	Developing the right mix for different printers would be challenging.
	TE-BR3	Labour (Architects, structural engineers, material engineers) force must be Reskilled to working with 3DCP.
	TE-BR4	With manual integration of reinforcement in vertical direction. Concrete is functioning well with compression forces, but not do well with tensile forces.
	TE-BR5	Developing the right mix complying the local temperature would be difficult to achieve.

	TE-BR6	Limitation in size of the printers. Thus, Limits in printing High rise building (2+ storeys).
	TE-BR7	No standard design tools for 3D concrete printing.
	TE-BR8	Hardening of concrete in a silo and hose if there is any technical error in the printing process.
	TE-BR9	Skill development for BIM integration, solving Interoperability issue with 3DCP and BIM software's.
	TE-BR10	Lack of research on the implementation of 3D printed house methods in the construction industry
	TE-BR11	Uncertainty in the life cycle of houses.
Environment	EN-BR1	Contractors have Lack of understanding in 3Dconcrete printing methods
	EN-BR2	There are no standard guidelines for 3D concrete printing
	EN-BR3	Lack of awareness of the benefits of 3D printing for housing delivery
	EN-BR4	Indian Construction industry is more conservative in nature.
	EN-BR5	There is not much room innovation in affordable sector, as delivering homes with keeping final cost and profit in mind is critical for investing in new technology
	EN-BR6	No incentives provided by the government for every company for adopting or developing innovative technology.
	EN-BR7	Incentives are given to proven low cost-effective technologies not much room for up bring new technology
	EN-BR8	Lot of time requirement in coming up with regulation. Many hierarchical advisory members in the evaluation committee who drag the issue of address the regulation. Again, this occurs due to less incentives and motivation to work on it
	EN-BR9	Developers do not invest much in R & D to try out new technologies
	EN-BR10	Late adoption of technology from private developers.
	EN-BR11	Procurement process: Low cost tendering another factor which hinders contractors in using new technology due to uncertainty
	EN-BR12	Not much collaboration opportunity/incentives with industries and educational institutes
Cost	CO-BR1	High investment costs in 3D printing technologies Many local developers view 3D printing as still high-priced investment
	CO-BR2	Indian industry is cost driven market.
	CO-BR3	Cost for reskilling and hiring skilled labours
	CO-BR4	Maintenance cost of robots
	CO-BR5	Material cost are 3 to 4 times higher than traditional concrete

Table 5:Consolidated list of barriers

4.3 CURRENT STATE OF ART:

Based on interviews, the current state of the art of technology, out of 9 respondents, 8 of them responded that the 3DCP at present is still in the research phase in the readiness level. Whereas an organization 2 responded that their technology had reached the commercial phase for constructing the houses. Besides, as far as educational institutes are concerned Indian institute of technology (IIT), madras, and Central Building Research Institute (CBRI) are one of few institutes focusing on active research on 3D concrete printing. As per the market is concerned, two 3D concrete printing companies have been commenced, and two large construction companies have adopted the technology. Moreover, many large companies are aware of the technologies, and smaller companies think technology is costly or have no awareness of the technology. Notably, till today few toilet modules are printed by the researching institutes and companies as part of prototyping projects achieving an average height of 1.5m-2m. One such example is shown in Figure 9. Many of the institutes and companies focusing on 3D concrete printing research have a gantry set up, and one company has leased out a robotic arm printer. The average Printer size is 11m X 2.5m X 2.5 m. The prototyping houses, and toilet modules are or to be built are printed as a module and then assembled on site. Printing speed by robots is about 100mm to 200mm/sec; besides, the printing speed can be changed according to the consistency of the material. Combining mechanical properties and mix design, the precision level achieved is to up to 0.5mm to 1mm on an average. As for the reinforcement integration, it can be reported based on all interviews that a standard method was used in printing the prototypes. Which was to put the rebars into cavities after the printing would take place and the grouting the cavities. A respondent from organization 1 mentioned that this method has its limitation where it cannot be used in intricate construction designs.

Figure 9: 3D printed room module at IIT, madras. Source: ETreality

As per the environment (E) dimensions are related, not many developers in the affordable housing market are willing to take up the research in 3D concrete printing. However, according to organization 1, few cement companies were interested in coming up with the right mix for the technology in collaboration with researching institutes. Moreover, the government bodies facilitating affordable housing under the mission "PMAY-Housing for all" have been putting efforts to attract, identify, and incubate new technology from across the globe to build affordable houses. So far, the government has identified 54 new technology for constructing affordable houses, out of which 3D concrete printing being one of them and has been given support for further development at the Indian Institute of Technology, Madras. As per the procurement is concerned, only proven cost-effective technology from the identified new technologies are procured for lighthouse projects, else procurement remains to be based on low cost. As per the cost (C) dimension, the printable concrete material is still very expensive at the moment. Four of the respondents see the costly material as a barrier for 3D printing adoption in construction. “Material costs are three to four times higher in our company”-organization 4. Contradictorily, organization 2 said

that “our material cost has reached the commercial phase, where the cost of material is drastically lowered than compared to the cost of other companies overseas. Moreover, organization 2 reported having achieved an estimate to construct the houses for ₹820 or €11 per square feet, which brings construction of houses to 25% cheaper than the traditional construction.” Furthermore, organization 4 added that the overall cost for setting up 3D concrete printing took about 2000 to 3000 us dollars and taking 10% of the invested amount for annual maintenance. Moreover, the company has been developing machinery for other contractors as well for improving the profits.

4.4 FUTURE VISION AND OPPORTUNITY FOR IMPLEMENTING 3D CONCRETE PRINTING FOR AFFORDABLE HOUSES

4.4.1 Opportunities

According to most of the respondents, the opportunity to replace the traditional construction methods such as monolithic construction (which is widely adopted for constructing affordable houses in India) with 3D concrete printing would be the freeform of design. Were the affordable sector could customize the design with the help of 3D concrete printing technology, where it was not possible with prefab/aluminum formwork construction. Moreover, according to organizations 1, 4, and 9, once the technology is fully developed. Complete automation in construction will cut down labor by 70%, which increases the quality of work and reduction in the overall cost of the house.

Moreover, government support for bringing innovative technology shows the opportunity to use 3D concrete printing for low-cost housing. According to organization 2, it has got tender by the local state government to build 200 houses using 3D concrete printing technology. According to organization 4, the respondent mentioned that the opportunity of using 3D concrete printing is now focused on to affordable housing sector. However, organizations see significant opportunities at this moment to print luxury homes for clients who are willing to pay a premium to use new technology. Moreover, the organization sees an opportunity in many infrastructure projects, for example, bridges and opportunities in printing many interiors, durable furniture. According to respondent 3, a more significant way for 3D concrete printing to integrate to countrywide would be matching 3D concrete printing with kutcha housing methodology, where the kutcha houses are made up of locally available mud, straw, wood and involving local skilled labor’s.

4.4.2 Vision

Based on the data analysis, several technical and non-technical challenges were identified in the current scenario in the Indian construction market, which may hinder the development of 3D concrete printing technology and market success. Thus, the following technology, cost, and environment factors vision must be taken into account by the contractors in the future to integrate the technology for constructing affordable houses. It is envisioned that the contractors shift from using traditional formwork construction to using 3D concrete printing as a method to construct affordable houses in 10 years. In order to see the vision happening, the contractor and industry key player must adopt the following vision strategies and act considerably to fully integrate the technology into the construction industry to achieve the vision of printing affordable houses.

Technology dimension: Technology is in a state to print large scale houses using local, affordable, and advanced materials with structural reliability withholding specific seismic loads, together with faster printing, sizable, and cost-effective manufacturing processes. Further technology achieves automated monitoring, reinforcement integration, and control mechanisms. Additionally, incorporating advanced and composed design information modeling and topology optimization will boost the overall speed of construction using minimum materials, which is an essential factor in meeting the gap in the affordable segment.

Cost dimension: 3D concrete printing robots are accessible at a lower price. Small and medium-sized developers that are in limited resources should be able to adopt the technology with a novel business model. Hence available of reliable, low-cost printers, usable by the local skilled workforce with sound financial backing, will help both large and medium scale contractors in faster adoption of the technology. Moreover, 3D concrete printing is still perceived too much as a technology solution instead of a business solution, hence effective business models with finances are available by technology providers to partner with local contractors.

Environment dimension: Standard building codes for 3D concrete printing are included in the Indian standards codebook for the uptake of technologies. Moreover, in order to provide manufacturers with the most excellent opportunity to exploit 3D concrete printing technology and provide confidence to manufactures and end-users, the government has come up with innovative procurement strategies, which include the use of new technology for constructing houses. Additionally, early publication of 3DCP certification guidelines is established, so that printer and printed houses are safe, reliable, and robust for gaining the trust in the technology.

Education and training: proper communication campaigns, industry involvement in education, and training aspects were delivering proper learning content at all levels. Such as, specific educational programs, workplace training, on-line education, and reskilling actions for the current workforce are effectively implemented for understanding the technology, thereby making the mark of the adoption process.

4.5 ROADMAP

Aim of the roadmap is to provide a fixed sequence of actions and recommendations for the contractors in India, to adopt the 3D concrete technology for constructing affordable houses successfully.

4.5.1 Background

The roadmap includes three primary layers that emerged from the literature, which is shown in Figure 10 below. Thus, Roadmap in this report discusses the step-by-step development of technology, focusing on the Technology, Product, and Market (TPM) layers incorporating the barriers, enablers, and opportunities identified in data analysis according to TEC dimensions. The work involved the development of a procedure linking the triplet TPM that provides the contractor an opportunity to understand and, thus, be able to better plan and construct houses using 3D printing technology. Thus, with this scientific contribution, contractors in India can use this tool to adopt technological advances to construct affordable houses.

Phase 1: Technologies: The technology layer describes the most promising technologies within a specific time scale. It provides a SWOT-analysis of these technologies highlighting the benefits and limitations technology. It also includes a forecast of target properties required to satisfy market needs and a set of the main tasks necessary to achieve these properties (Vishnevskiy et al., 2016). In the final analysis, it allows illustrating the technology's prospects in terms of readiness for implementation and potential effect.

Thus, in this phase, contractors should primarily focus on researching refining technology applications and prepare for a comprehensive pilot study. Moreover, the contractor has to establish partnerships with technology providers with a cost-effective contract for carrying out a pilot project.

Phase 2: Products: This layer contains a brief description of prospective products in terms of readiness for commercialization and potential impact on the respective research field. It also estimates the time needed for commercialization and the most prospective market positions for each product. Thus, in this phase, the contractor should allocate the second phase to perform the pilot study to develop the product and audit it for barriers and enablers. Administrating of talent acquisition and capacity building at an organization level should be addressed.

Phase 3: Markets: The methodological approach implied in this layer is two scenarios of potential market development consisting of optimistic and moderate (sometimes also referred to as 'realistic' or 'base case'). Scenarios provide an opportunity to consider the technological and product development that is reflected in layers 1 and 2 (Vishnevskiy et al., 2016). As a result, contractors must take the third phase to be the longest, for actual integration and implementation of the 3D concrete printing technology of houses on the local level and addressing issues of scaling up operations to the markets.

Start condition of the roadmap

Implementing the vision will cost both money and time, coming from different parts of the project. The significant expenses will be buying or leasing the 3D printing robots, silo, mixer, hiring trained employees, buying relevant software, hardware, and recurring expense on additive concrete. Since there is not much cost allocated for R&D in the contractor's organization, especially in the affordable housing segment, hence the contractors need to collaborate with the technology providers. Collaboration could be carried out with comprehensible innovative business models for the adoption of 3D concrete printing technology. Furthermore, down the timeline of implementation of 3D concrete printing, contractors should look at additional revenues through a service business model to train and help adapt the technology to the unaware contractors. Many states in India and other developing countries do have a more significant market for affordable housing. Contractors can provide technical assistance, and consulting will bring in extra revenue to the supplement core business and increase the reputation of the organization as well

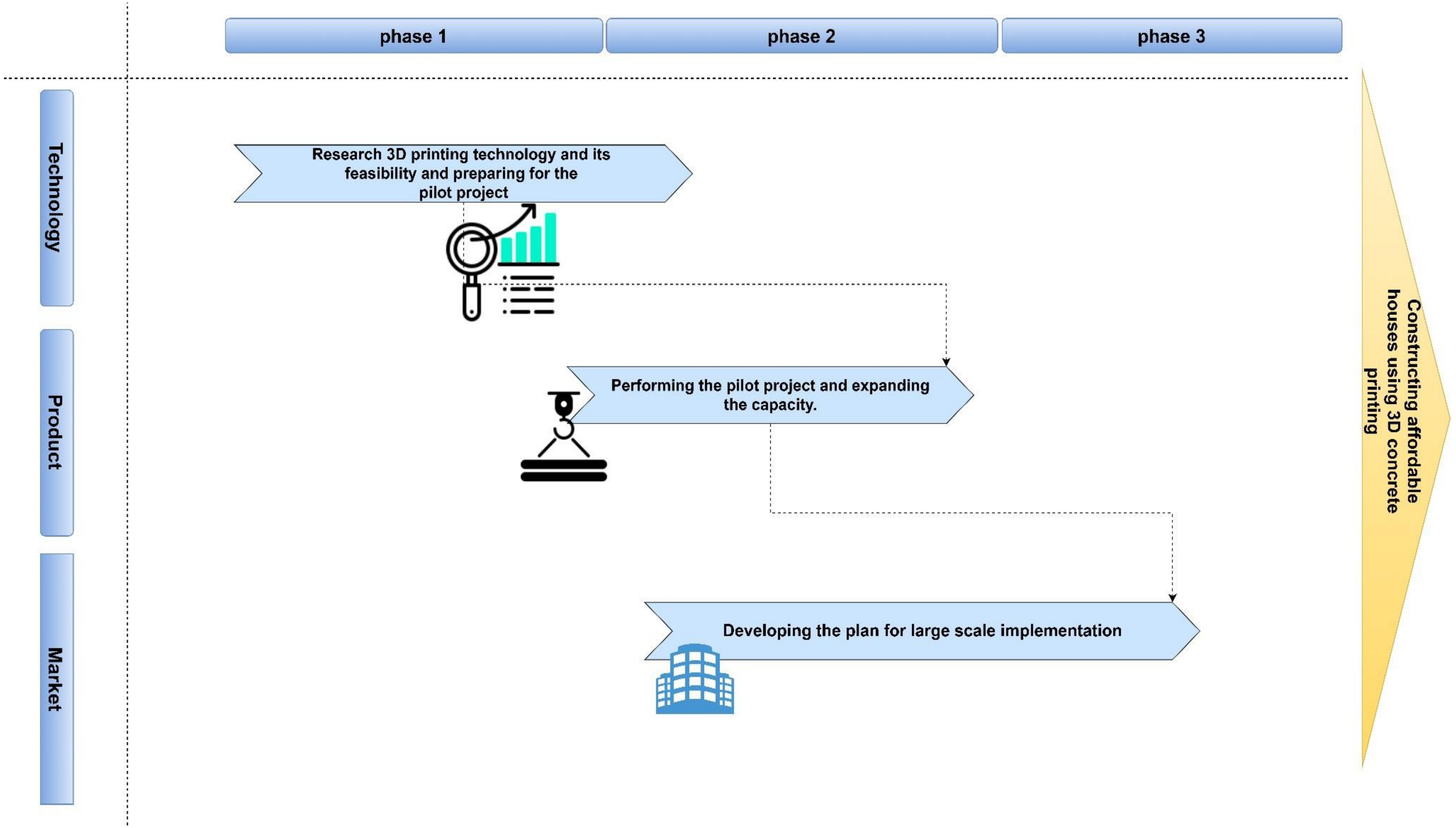


Figure 10:A condensed roadmap for the adoption of 3D concrete printing by contractors in India.

4.5.2 Action to be taken by the contractors in phase 1:

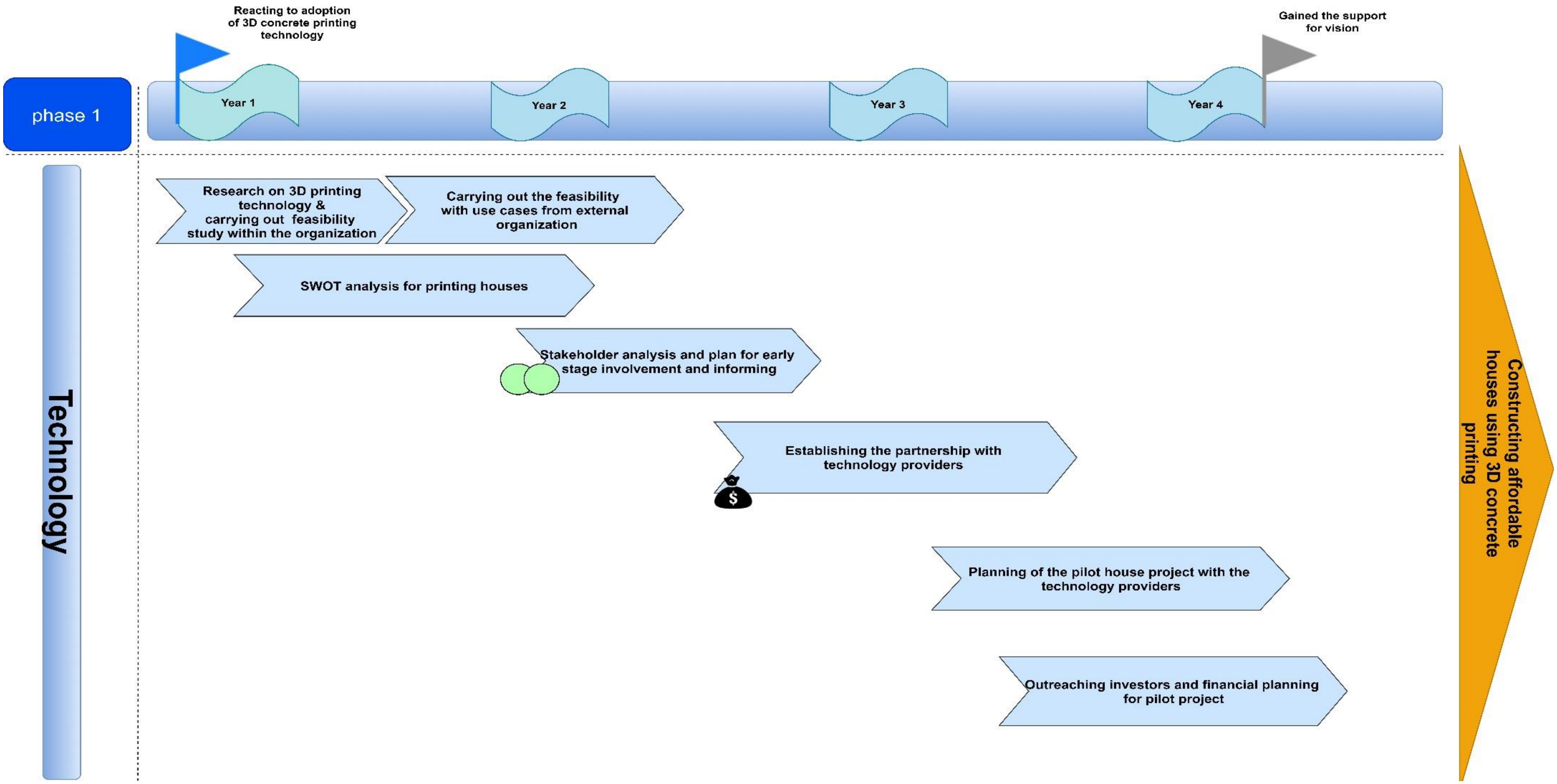


Figure 11:Roadmap for technological phase

Carrying out Research and feasibility of 3D concrete printing houses.

The first four steps of Figure 11 indicate carrying the feasibility study over the period. Concerning the barriers EN-BR1, EN-BR3, and EN-BR4, contractors should start by carrying out the feasibility study within the company. Further, a small budget has to be created from the centrally available budget to carry out an extensive feasibility study with use cases from the external consultants, to get added insights on the technology. Later a SWOT analysis must be carried out on using 3D concrete printing for constructing the houses. Furthermore, stakeholder analysis must be carried out in order to find out key people, organizations, and those who will be affected by the implementation of the technology. At this stage, the extensive feasibility study carried out will help to convince the stakeholders that are responsible for the market vision, or able, to create the central budget. Contractors should make sure that, from the first moment on, the people authorized for making this decision are considered this averts delays and stagnation in the implementation process.

Establishing a partnership with technology providers to get access to technology:

As discussed in the start condition of the roadmap, purchasing the technology at this point in phase would be costly for a contractor addressing EN-BR9 and EN-BR10. Hence the contractor has to build up the partnership with technology providing company as shown in Figure 11, with the new business model in order to help understand the technology and to start with a pilot project. Once the partnership is set up, final collaborative research should be done on the technical applications. Following this research, a plan must be made for a pilot project on the chosen technical methods of printing to be carried out in the subsequent stage. For the realization of these pilot studies, monetary resources are essential. Being realized by the benefits of the technological implementation's contractors should put aside a specific available budget for the project and further should outreach the investors for further financial planning.

4.5.3 Action to be taken by the contractors in phase 2:

Initiating the process to print pilothouse

Contractors, along with technology partners, are required to map the site layout for assessing soil conditions and suitable foundation to install or printing 3D printing structures as streamlined in Figure 12 and further shown detailed in Figure 13. Moreover, the company should assess the suitable slab and installation methods for the printed modules or printer itself. Once the layout planning is finalized, the final design calculation should be optimized based on the strategies towards possible alignment with the existing Indian standard building. Later the design is converted into printer readable codes for printing the structure. The next step would be installing a printer on or off-site according to plan with the technology provider and initiate the process of printing the pilothouse. As a result of using a 3D printed pilothouse, the contractor has to determine the exact pros and cons at the ground level of the project and validate with codes TE-E and TE-BR. By measuring the costs, the time of the pilot project can advance the feasibility study, and the contractor can make improvements accordingly to move on to the next projects. Once evaluating the technology benefits with the pilot project, the contractors should approach the government bodies for the appraisal for recognizing and building standards, as mentioned in codes EN-E2 and EN-E3.

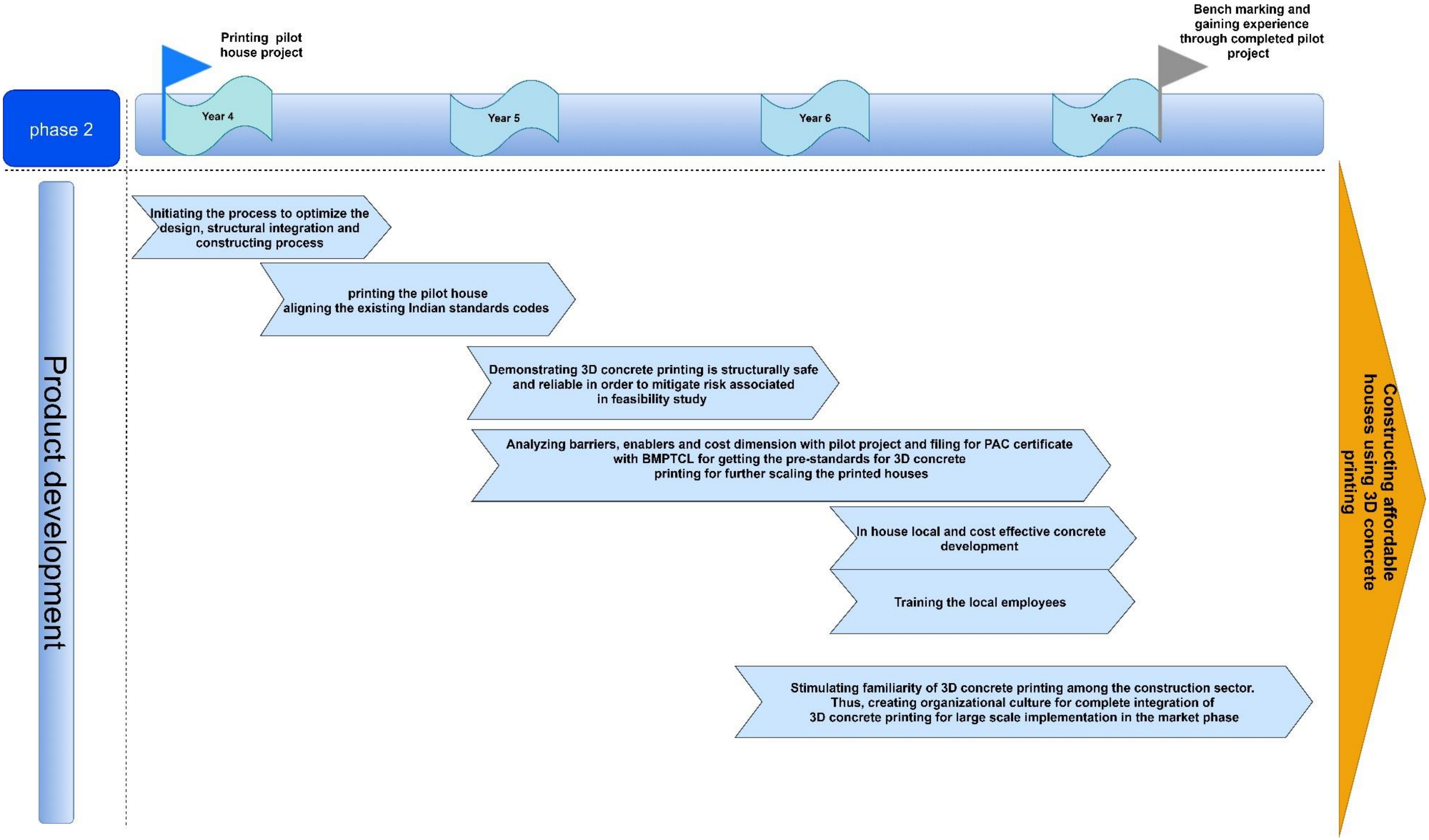


Figure 12:Roadmap for the product development phase

Government bodies such as Building Materials and Technology Promotion Council (BMTPCL) bridges the gap between research and development and large-scale market application of new building technologies. Thus, BMPTCL will help evaluate and validate the structural performance of technology, and the contractor can have the performance appraisal certificate (PAC) certificate. Which will be a pre-standard certificate with this any local or foreign company can start doing business in the affordable sector. Contractors at the same time should consider barrier codes CO-BR5, TE-BR3, and TE-BR9, in developing cost-effective materials, reskilling employees in collaboration with technology providers. Furthermore, reflecting on codes TE-BR2, TE-BR5, and TE-BR8, the interaction between material properties and 3DCP processes like rheology, shear rate, fast solidification, binding between layers, shrinkage. Materials with such properties have to be considered and developed by meeting different climatic conditions and printing parameters in order to increase the adoption rate in every region of the country. Moreover, taking the code TE-BR4 into account, Investigation and assessment must be carried out for reinforcement materials (e.g., steel, glass, carbon, natural fibers) and development of applying it into printing material. Thus, the fiber distribution concerning tensile (and bending) properties has to be looked upon for printing the mass houses with a different design parameter. Hybrid technologies for instance post processes like placing external and internal tensile rods should be considered for creating structurally safe and reliable houses.

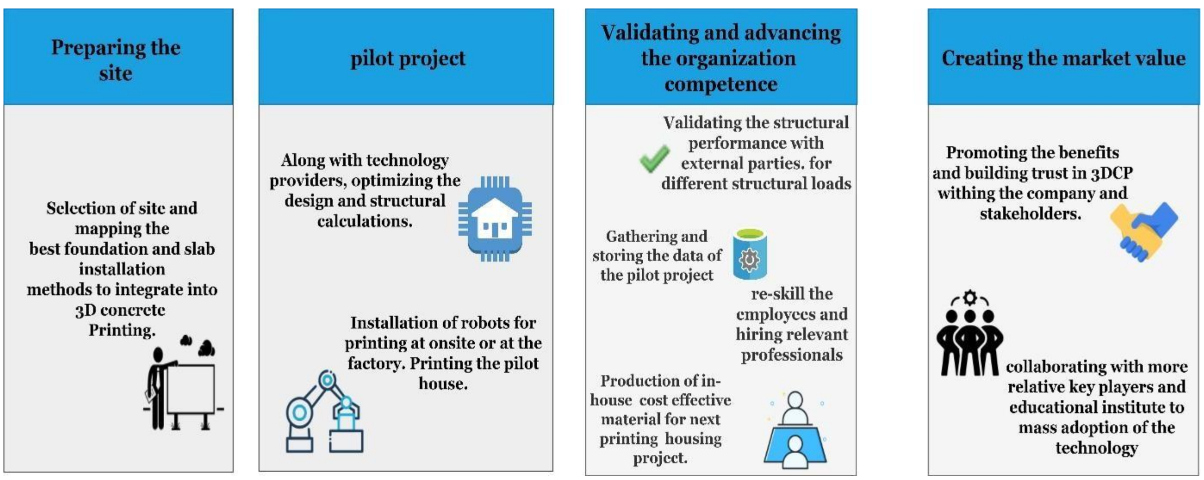


Figure 13:Details steps of phase 2

Before heading on to the next phase, reflecting on the codes EN-BR2, the contractor needs to show positive behavior by promoting the benefits so that everyone in the Indian construction industry is familiar with 3DCP, unusually affordable market sector developers as indicated in the last step of Figure 13. They need not know all the prerequisites; nevertheless, they must be aware of the concept and know what is going on with the technology. Awareness can be ensured by including the 3DCP concept in the overall vision, ideas, and having a strategy concerning technology awareness with other organizations. Furthermore, collaborating with educational institutes offering presentations, undertaking courses, and organizing conference events can be valuable additions in the process of making 3D concrete printing familiar. 3D concrete printing technology should be brought to the developers (preferably by experts with hands-on experience). Hands-on experience of technology gives a chance to feel technology and learn its added value. An experience stimulates acceptance and willingness to use technology. Knowledge sharing throughout the whole industry facilitates even faster adoption and development on the market level.

4.5.4 Action to be taken by the contractors in phase 3:

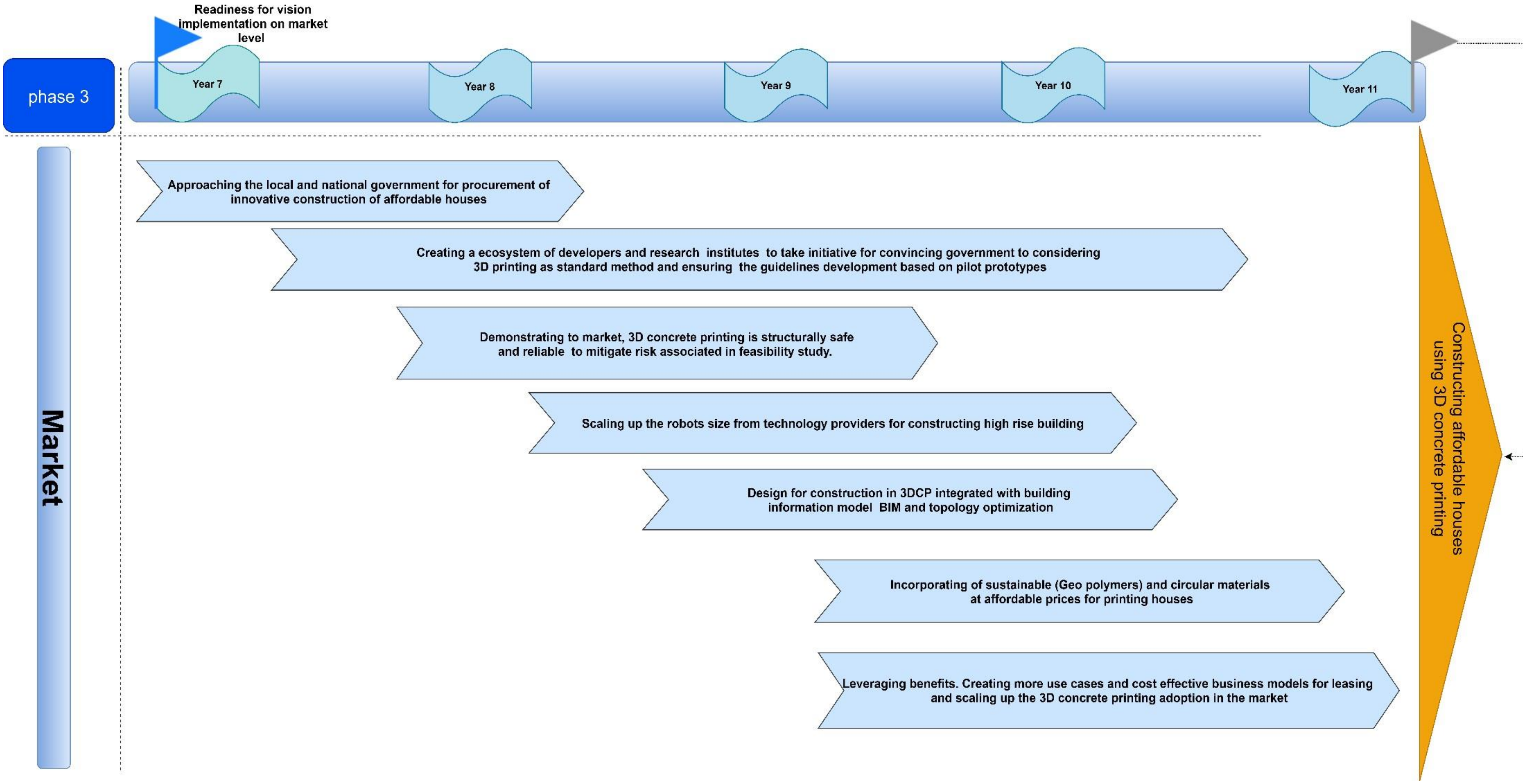


Figure 14:Roadmap for market integration

Once establishing the familiarity in the market steps shown in Figure 14 has to be followed, which can be achieved based on pilot project demonstration and feasibility study for constructing the houses. Contractors have to approach the local and state government in order to get the tenders for constructing houses. Moreover, contractors with their collaborators and other players using 3D printing have to form an ecosystem or join the ecosystem in order to promote and pressurize the government sectors to make the standardization and recommending to push the technology through innovative procurement. This way, there will be a huge demand created in the industry and thus improving the technology at the market level.

Entering the market of constructing the houses, taking the code TE-BR6 into account, contractors should further start scaling up the robots for optimum utilization of land at the affordable market level. Since the currently used concrete printing equipment are capable of printing one to a maximum two-story house. Besides, an improvement step should be taken regarding speed, control, accuracy, adaptability, and transportability. Concerning machinery development, contractors need to learn and lean from experience in another sector. That is to encouraging machine and equipment manufacturers from outside the construction field to engage and develop concepts/demo projects needed for large scale printing.

Moreover, contractors should learn how to put all the information into a single source and design the part positions by software optimizing deposition paths to minimize delays and optimum usage of materials. This can be achieved by design for construction in 3D concrete printing integrated with building information model (BIM) and topology optimization. This way, contractors can have a digital representation of all physical and functional properties with a shared knowledge source with information on the building, which can be used as a reliable basis during the whole life cycle of the building. Since there are many software tools to work on 3DCP, new standard BIM design rules must be developed in order to couple with automatic processes/materials/functionality. Integration with the currently used Building Information Modelling (BIM) system will showcase the more significant benefits. In the later stage of reaching certain market maturity, acting on code TE-E5, the contractor should start Incorporating sustainable (Geo polymers) and circular materials for printing houses. Creating an affordable, sustainable mix design using materials such as geopolymers, fiber-reinforced polymers. Moreover, developing the mix design using the construction waste material should be incorporated in printing houses, which would reduce the waste and carbon-producing materials.

Furthermore, addressing the barrier code EN-BR4, the construction industry is known as a relatively conservative industry. Hence, making it difficult to change the current way of working. Contractors need to take steps in proving by positive use cases at the market level creates trust and confidence for using the technology by the other contractors. This way, the contractor can leverage benefits by the introduction of the 3D concrete printing technology in small manageable steps for the other companies with a good business model to adjust and adapt the 3D concrete printing technology. Thus, allowing for smoother adoption of the new technology at the industry level.

4.6 VALIDATION OF THE RESEARCH

After completion of the roadmap, a developed roadmap was shared with contractors, 3D concrete printing companies experts, and developers who showed keen interest in using 3D concrete printing and other digital technologies as part of their organization. These experts were asked to validate the roadmap based on specific requirements that were derived from literature as shown in Table 6. For validation of the roadmap, the company experts were asked to rank with the qualitative score for each requirement ranging from Strong, neutral, and weaker. Accordingly, these requirements, along with roadmap, were put on goggle forms and were sent to the experts mentioned above. The following table depicts the level of importance the roadmap has on each requirement derived from an expert's understanding. The feedback from the contractors was to provide more insights and potential validation and not altering the final roadmap actions developed for the contractors.

SL.no	Requirements	Qualitative Score		
	TPM roadmap	**Strong**	**Neutral**	**weak**
1	**Completeness** (The developed roadmap includes the relevant technology, regulations, and cost dimension strategies to cope with the uncertainty in the internal and external environment for the adoption of 3DCP)	3		
2	**Areas of future actions** (The roadmap developed process gives direction to future innovations by defining multiple strategically essential areas and actions to adopt 3D concrete printing into organizations).	2	1	
3	**Easiness to understand** (The roadmap drafted is suitable for communication and thus, easy to understand)	3		
4	**Usability** (The roadmap process is simple to execute with understandable activities in each layer)	2	1	
5	**Adaptability** (The roadmap process is practically applicable and is flexible to add new factor/dimensions to keep the necessary time and effort limited)	2	1	
6	**Realizability** (The roadmap timeline of 10 years and activities drafted can be implemented realistically)	3		
7	**Suitability** (The structure of the roadmap and the adoption actions mentioned enhances the implementation of 3D concrete printing by Indian contractors)	3		

Table 6:Validation of the roadmap

- Strong: Requirements of the roadmap are strongly agreed
- Neutral: Requirements of roadmap partially agreed with strong and weak scores. (Few improvements needed)
- Weak: Requirements of the roadmap are weakly agreed.

Based on validation, there were few different viewpoints on steps that were developed in the roadmap, as it can be seen in the table that most of the experts have expressed a strong opinion to the maximum of requirements on the developed roadmap. Moreover, it has stated that roadmap includes all the relevant information that the contractors need in knowing internal and external action for adopting the technology. However, there was supportive and some specific contradicting feedback on using the roadmap. The main feedback was to investigate and develop the roadmap from the holistic perspective rather than just contractors, which is to consider all the stakeholders into account as decision-making strategies for the adoption of 3D concrete printing. Feedback can be briefed as below

- The client should be considered as the primary stakeholder in the application of technology, the client, who generates the willingness to use 3D concrete printing. Since the client frames most of the project briefing and the technical specifications, very few clients seek fresh inputs from the contractor. Therefore, the above validation gives the research clarification to consider the customer as crucial stakeholders by contractors in adopting 3D concrete printing technology.
- Innovation driver often comes from the local ecosystem. Switching costs in the local ecosystem impedes innovation, and local contractors believe that it is not a good idea to push any new technology when there is not a buyer for it. For example, ready mixed concrete (RMC) in India and many other countries became a huge success. And it took less time to embrace it in India as there was a local customer need to simplify things where producers understood the vast benefits on offer.

However, two out of three respondents agreed that the roadmap is helpful with no contradicting points, which can be concluded that developed roadmap is validated and suitable for contractors in improving the knowledge and reducing the uncertainty in adopting 3D concrete technology. Moreover, the importance of this validation helped the author to investigate more in-depth, drawing conclusions, scientific limitations, and drafting future work.

5. DISCUSSION:

Reflection on 3D concrete printing in Indian Industry

In the current situation of the Indian construction industry, 3D concrete printing technology, some degree has caught attention to all the key players from government, contractors to educational institutes. However, only a few companies have taken the initiative to adopt the technology. Based on the data collected, it can be reflected that 3D concrete printing in the Indian market is still at the research phase at the readiness level. Moreover, the central vision of each organization was ultimately to print houses at an affordable cost. Even the government bodies concerning the development of affordable houses have identified 3D concrete printing as an innovative technology for constructing houses and has given incubation support for further development.

Additionally, many large companies are aware of the technologies, and small-scale contractors think that technology is costly or have no awareness of the technology. Notably, until today, few room modules, as shown in Figure 9, are printed by the researching institutes and companies as part of prototyping projects achieving an average height of 1.5m-2m. Moreover, with such a prototyping project, the respondents see 3D concrete printing technology as an opportunity to solve the current problem regarding the scalability and scarcity of skilled workers in constructing large scale housing projects.

Reflection on Road-mapping relationship between technology product and market

This research provides a decision-making contribution through the development of a three-layered roadmap; this developed roadmap can be referred by both industry and the public sector in India. The developed roadmap visualizes representation of how the relationship on technology, product, and the market should be considered by contractor overtime to implement 3D concrete printing for constructing affordable houses. The developed roadmap is a time-based graph that consists of multiple layers, namely technology, product, and market, that provides external and internal actions for implementing and developing 3D concrete printing. Such as action to be taken by the firm internally to develop the technology that fits the market needs and steps that the company can use external drivers, for instance, government policies and technology providers (innovators) strategies that strengthen the firm decision in the adoption of 3D concrete printing. Thus, developed three-stage business roadmap process is considered appropriate, inspiring, and valuable to severe the affordable markets by delivering the houses using novel 3D concrete printing technology. First, roadmap emphasizes that contractors should think before adopting as it involves a detailed feasibility study and SWOT analysis concerning implementation issues and gives attention to acquiring support. Next, executing planning through developing a product roadmap, which is considered a valid and efficient, the actions in the product development, a contractor allocates the product phase to perform the pilot study to develop the product and audit it for barriers and enablers.

Moreover, administrating talent acquisition and capacity building at an organization level is addressed in the product development phase; this reduces state and effect uncertainty. By distinguishing between technology focus areas and product development phase, the road mapping process, moreover, yields useful results as the preconditions that always need attention, which cannot be neglected. This further clears out uncertainties in approaching the market niche, where a contractor can use the product development phase to demonstrate and procure the affordable housing development or can approach the client in developing luxury homes. To conclude, the process gives rough steps a contractor must undertake, leaving space for multiple pragmatic interpretations to approach and fill the market demands.

Reflection on the adoption factors.

In addition to the three-layered roadmap for decision making, this study provides evidence that perceptions including, technology, environment, and cost factors, are found to be significant drivers of intention-to-adopt 3D concrete printing. However, there were many factors found during the interview process, for instance, communicational, Informational, awareness. Nevertheless, all these factors were possible to categorize under the TEC dimensions.

Concerning the technology (T) factor, given the size of the printers and printing speed, the main enablers that were brought up are reduction in construction time, quality of construction, more architecture freedom, reduction in labors. However, a significant proportion of technology barriers are yet to be addressed in the next phase of technology development, for example, a less-known method for concrete reinforcement integration, the small size of the printers, the high cost of additive concrete and missing regulating codes for 3D concrete printing. These were the most notable barriers which were hindering in bringing the technology to the commercial phase.

Inspecting on environment (E) factor, all organizations agree upon the fact that government support can encourage the adoption of 3D concrete printing technology. Moreover, they agree that the government must take the first step by introducing regulations, incentives, and awareness to help adopt the technology in the Indian construction industry. Besides, organizations see the fact that there are no standard regulations yet regarding the 3D printing technology in construction, thus view this as a significant barrier. Furthermore, barriers for instance lack of awareness of the benefits of 3D printing for housing delivery, conservative nature of the construction industry, contractors delivering the affordable houses operated on a thin margin of profit, and no incentives are provided by the government for every company for adopting or developing innovative technology. These barriers are some reasons for hindering the adoption of technology by the contractors.

Concerning the cost (C) factors, it became apparent during the interviews that the 3D printing concrete material is still costly compared to traditional concrete. Which, according to the cost factor, material cost was the highest recurring cost. Thus, currently making the overall production more expensive. However, 3D concrete printing technology only needs the minimum required amount of materials, according to Wu et al. (2016), which introduced as ‘topology-optimization’ in the interviews, which can compensate for the overpriced material. Furthermore, the cost of a 3D printer for construction purposes is not low, which was confirmed by the organizations interviewed. However, the contractor can note that this is a one-time investment from which the company can profit for several years. As stated by Jha (2012) states that 35 to 54% of the total construction costs can come from the formwork. As 3D printing can eliminate the expensive formwork, this cost can be significantly reduced, as verified during some interviews. Moreover, organizations claim that 3D concrete printing reduces supply chain and transportation costs.

Contribution of the research

The main contribution of the research is systematically analyzing the current market and state of the art of 3D concrete printing technology and its opportunities in the Indian construction industry. Moreover, providing a detailed, validated, and usable roadmap on how the different contractors could use and contribute to further advancing 3D concrete printing technology in the Indian context.

Further, this research adds to the literature of the adoption framework. The technology-organization-environment- cost (TOEC) framework, which was modified by Yeh, C. C., & Chen, Y. F. 2018, on the basis TOE framework originally developed by Tornatzky and Fleischer (1990), was used as the foundation for carrying out the research. However, a roadmap being developed from the academic-industry perspective were any contractors or developers could make use of the research in adopting the technology. Hence organizational dimensions were overlooked. Therefore, the TEC framework became the basis for collecting the data and was found to be significant in gathering all information that the industry needs in knowing and adopting the technology.

Besides, clarifying the main factors influencing the adoption of 3D concrete printing, and this study contributes a validated business roadmap for implementing 3D concrete printing in a contractor's firm. It can be noted that roadmap development in three layers on acquiring technology to the market application has been validated by construction companies to be usable, easy to understand, realizable, and suitable for the adoption of technology. As a result, this study serves as a primary reference for adopting 3D concrete printing in any country. Reference could be achieved by following the similar steps of the roadmap along with assessing the state of technology in an adopting country. Which such assessment, given the regulation support and technology development of the country, may lead to different timelines of the roadmap for adopting the technology.

6. CONCLUSIONS

The research objective of this study was to develop a roadmap towards the successful implementation of 3D concrete printing by contractors and thereby wider adoption. Thus, identifying the potential of 3D concrete printing within the Indian construction industry for constructing affordable houses. Literature research and interviews were used as two primary data sources for answering the four sub research questions, thus formed the basis for qualitative research. Data collection for this research, the technology-environment-cost framework, abbreviated to the TEC framework, turned out to be an excellent adoption model to use and analyze the adoption behavior of construction companies in India concerning the 3D concrete printing technology. According to the adoption framework factors, diverse key interviewees were chosen from the government sector, contractors, 3D concrete companies, researchers, and educational institutes to deepen the understanding of 3D concrete printing. Everything the interviewees mentioned during the interviews could be classified under one of the three contexts of the model. The main finding of the research is categorized and analyzed into four sub-chapters, which are enablers, barriers, the current state of the art and opportunities of 3D concrete printing in the Indian construction industry. Further, these sub-chapters became the input for roadmap development, thus answering the main research question. The developed roadmap provides a decision framework using three-layer (Technology, product, and market) road mapping techniques. This helps contractors in implementing technology into their firm and further integrating it into the market.

The main conclusion drawn can be categorized as follows:

- The modified framework in this research proved to be an efficient means to study the adoption of disruptive technologies in the construction industry. As the framework considers multiple dimensions, thus showed potential in analyzing the adoption of 3D concrete printing technology, which provides valuable contributions to contractors for understanding the technology and nature in the Indian context. This study can be used for similar types of research when disruptive technology is being scrutinized in a new context.
- The proposed roadmap hence is proven to be scalable, adaptable, easy to understand, and realizable. Thus, contractors can see value in it and work on it for advancing it to the wider scale of adoption. A primary benefit of this developed roadmap is that it gives the contractors a comprehensive overview of the relations between developing technology to product development and approaching the market. Distinguishingly, it provides an insight into the time component gives an overview of how the technology can be taken into a firm's strategy over both in the short term and the long-term.
- Indian industry's reverence for digital technologies and 3D concrete printing is advancing rapidly, but still, some barriers must be weakened for faster adoption and constructing affordable houses. As many affordable housing contractors in India work on thin profit margins with limited resources, the widespread adoption of 3D concrete printing would produce a significant influence on the construction industry, by using unique technology for constructing houses faster than traditional techniques. As stated above, the identification of main factors for its implementation provides valuable contributions to contractors and their decision-making process of whether or not to go in this direction.

6.1 IMPACT ON BUSINESS IMPLICATIONS

Roadmap implication by companies in India still has major value propositions for contractors using 3D concrete printing. For instance, the construction of mass houses can be customized, and houses can be constructed much faster with increase in the quality of construction, and an increase in the safety of construction houses.

Impact on adopting 3D concrete printing on heading affordable business applications has many anxieties to the countries like India that needs to be considered. The main undetermined factor is, developing 3D concrete printing technology will take jobs from many local trained labors. Gaining insights from the in-depth interviews, it became clear that it is hard to achieve a complete replacement of traditional construction methods with 3D concrete printing in the next few years. It is possible, 3D printing may be developed along with the traditional techniques, supporting them, especially in case of more sophisticated building projects. Moreover, 3D concrete printing at the moment is most used for wall construction. This explains that the installation of foundation, roof, MEP, and finishing is done with manual work, which does not eliminate the labor work entirely.

Furthermore, space is a premium in urban areas. Consequently, India has witnessed the construction of many high-rise structures for affordable housing segments predominantly with cast-in-situ concrete and rarely with precast concrete. This can be witnessed in both affordable and luxury housing segments in urban cities. Such as Mumbai, Delhi, and Bangalore. Based on the readiness of the technology, 3D printing of high-rise buildings is just far to achieve, which leads to minimum utilization of land. Thus, this might create a barrier to implementing technology in urban areas. However, based on the insights generated from the research, it becomes clear that the contractors can make use of 3D concrete printing in semi-rural and rural areas to print one to two-story houses to make use of technology advantages.

Moreover, COVID-19 lockdown has exposed many chinks in the Indian construction industry, which relies heavily on migrant labor from rural areas for workers, and many contractors are now working towards automation process techniques, which helps in easier adoption of 3D concrete printing. Nevertheless, the construction industry world over is known for reticence to change in either technology or materials, and any driver for change often should come from the local ecosystem with support from the government and education sector.

6.2 LIMITATION OF RESEARCH

Although this study has contributed to both theory and practice, there are still some limitations.

First, because this study applies to the TEC framework that incorporates the technology, cost, and environment factor for the evaluation and adoption of 3D printing, some specific dimensions and criteria might have been overlooked. Future researchers can investigate this issue from the perspective of other factors that might affect the adoption of technology. Second, this study was carried out with opinions from a small number of experts. Therefore, further research focusing on a larger sample and unobserved stakeholders should be able to increase the reliability of this study. Another limitation stressed by many authors is the time and effort necessary for business road mapping, mainly to keep it alive (R. Siebelink, 2013). The main reason for the need to iterate the process is that the business roadmap is only valid at the time of publication (R. Siebelink, 2013). The business roadmap, namely, has a linear tendency and thus assumes a certain level of predictability and certainty about the future, which makes it weak for coping with changing circumstances (R. Siebelink, 2013). Since 3D concrete printing technology is still in the research phase, therefore in the coming year's technology will advance many directions. This results in altering the future work on the roadmap to achieve the vision quicker. So, regularly updating the business roadmap is necessary to reflect the changing circumstances the firm faces over time (R. Siebelink, 2013). Thus, the limitation can be argued that maintaining and manipulating a business roadmap itself is very labor-intensive.

6.3 FUTURE RESEARCH DIRECTIONS

This research delivers a holistic roadmap for all the companies that are interested in adopting 3D concrete printing technology. As a result, company can use the roadmap as a reference for streamlining the adoption of technology into their organizations. Thus, roadmap presented leans towards a more general framework. Future research may include developing and altering the roadmap adhering to a specific company, which helps in understanding the hurdles and benefits that a particular company faces in adopting the technology. Besides, based on the feedback received during the validation, it would be interesting for further studies to investigate the downstream side of the company as well, i.e., customer relationships and customer involvement. By doing so, knowledge and input from the customers can be seized, helping the company to develop product offerings based on the 3D concrete printing technology to create the incentives needed for upscaling 3D concrete printing usage.

Additionally, future work associated with this research can involve technical and non-technical contributions by picking up a barrier on each TEC dimension. For instance, research on assisting regulating bodies for developing a framework for building standards for 3D concrete printing, incorporating automatic reinforcement methods, developing a sustainable and affordable mix design, more innovative business models with technology providers and contractors, integrating BIM with 3D concrete printing. Such researches help in strengthening the adoption of 3D concrete printing technology. 3D concrete printing provides the unique ability for manufacturing organizations to bring house construction closer to the end-consumer design needs, reduce waste in comparison with traditional construction methods, and enhance the innovative design. Thus, the future researcher can include how the contractor by adopting can take advantage of various benefits that 3D concrete printing offers in different construction projects.

References

Anjum, T., Dongre, P., & Nihar Nanyam, V. (2017). *Purview of 3DP in the Indian Built Environment Sector*.

BCG (The Boston consulting group). (2018). *Will 3D Printing Remodel the Construction Industry?*

Charmaz, K. (1983). *The grounded Theory Method: An Explication and Interpretation. In R. Emerson, Contemporary Field Research. Illinois: Waveland Press Inc*.

COMTEX. (2019, 22 april). 3D Concrete Printing Market 2019 Global Industry - Key Players, Size, Trends, Opportunities, Growth Analysis and Forecast to 2025.

Ellen MacArthur Foundation, & ARUP. (2018). *THE CIRCULAR ECONOMY OPPORTUNITY FOR URBAN & INDUSTRIAL INNOVATION IN CHINA*.

Ellen MacArthur foundation, & ARUP. (2019). *CIRCULAR ECONOMY IN CITIES-A URBAN BUILDINGS SYSTEM SUMMARY*.

ET. (2018, 5 November). *"India's first 3D printed house may be built within a year.*

Golonka, A., Hager, I., & Putanowicz, R. (2016). *3D printing of buildings and building components as the future of sustainable construction?*

Hojati, Maryam & Nazarian, Shadi & Duarte, Jose & Radlińska, Aleksandra & Ashrafi, Negar & Craveiro, Flávio & Bilén, Sven. (2018). 3D Printing of Concrete: A Continuous Exploration of Mix Design and Printing Process.

Hulchanski, David, J. (1995). *The concept of housing affordability: Six contemporary uses of the housing expenditureto-income*.

ICON Pr. (2018). *New Story and ICON Unveil the First Permitted 3D-Printed Home | ICON*.

Indian development review. (2019, 22 mei). *The gaps and opportunities in low-income housing*.

Koslow, T. (2019, 9 november). 2019 Greatest 3D Printed Houses, Buildings & Structures.

Lojanica, V. (2018). *Housing of the Future: Housing Design of the Fourth Industrial Revolution*.

Lojanica, Vladimir & Damjanović, Vesna & Jankovic, Novica. (2018). Housing of the Future: Housing Design of the Fourth Industrial Revolution. 1-4. 10.1109/EFEA.2018.8617094.

Ministry of Housing and Urban Affairs (MoHUA). (2019). *Global Housing Technology Challenge- India (GHTC-India)*.

Mukhaimar, S., Makhool, S., & Samara, Q. (2014). *3D Printing Technology*.

Muylle, L. (2019). TECHNOLOGY READINESS AND ADOPTION OF 3D-PRINTING IN THE. 2018–2019.

Nadarajah, N. (2018). *Development of concrete 3D printing*.

Nematollahi, B., Xia, M., & Sanjayan, J. (2017). *Current Progress of 3D Concrete Printing Technologies*.

Ngo, Tuan & Kashani, Alireza & Imbalzano, Gabriele & Nguyen, Kate & Hui, David. (2018). Additive manufacturing (3D printing): A review of materials, methods, applications, and challenges. Composites Part B Engineering.

O'Neill, P. (2008). *Housing Affordability Literature Review and Affordable Housing Program Audit*.

Obudho, B. (2019, 9 oktober). 2019 Biggest Companies Building 3D Printed Houses.

Omar Geneidy, Walaa S.E. Ismaeel, Ayman Abbas. (2019). A critical review for applying three-dimensional concrete wall printing technology in Egypt (1758–9622).

Peng Wu, Xianbo Zhao, Hedi Baller, j, & Xiangyu Wang, (2018). Developing a conceptual framework to improve the implementation of 3D printing technology in the construction industry (1758–9622).

Peng Wua, JunWang, & XiangyuWang. (2016). A critical review of the use of 3-D printing in the construction industry.

Phaal, R., Farhuk, j p, & David Probert, R. (2004). Technology road mapping—A planning framework for evolution and revolution.

Pradhan Mantri Awas Yojana- Housing for All (Urban). (2015). *PMAY (U)*.

PTI. (2014, 13 april). *Shanghai Win Sun Decoration Design Engineering Co builds 10 3D-printed houses in a day!*

Ramakrishna, Nallathiga. (2010). *Affordable Housing in Urban Areas: The Need, Measures, and Interventions*.

Robert, p, David, R., & J.P. Farrukh, C. (2004). Technology roadmapping—A planning framework for evolution and revolution.

Saunders, S. (2017, 29 september). *Cazza Construction Technologies Introduces 3D Printing Construction Robots and Sees High Demand*.

Tahmasebinia, F., Raghava Reddy, K., & Marroquin, F. A. (2018). Three-Dimensional Printing Using Recycled High-Density Polyethylene: Technological Challenges and Future Directions for Construction.

Tay, Y. W. D., Panda, B., Paul, S. C., Noor Mohamed, N.A., Tan, M. J., & Leong, K. F. (2017). 3D printing trends in building and construction industry: a review. Virtual and Physical Prototyping,

Tay, Yi Wei Daniel & Panda, Biranchi & Paul, Suvash & Noor Mohamed, Nisar Ahamed & Tan, M.J. & Leong, Kah Fai. (2017). 3D printing trends in the building and construction industry: a review. Virtual and Physical Prototyping.

Tay, Yi Wei Daniel & Panda, Biranchi & Paul, Suvash & Noor Mohamed, Nisar Ahamed & Tan, M.J. & Leong, Kah Fai. (2017). 3D printing trends in building and construction industry: a review. Virtual and Physical Prototyping.

Tersteeg, R. (2018). GOVERNING CONSTRUCTION PROJECTS IN WHICH 3D PRINTING IS APPLIED.

The McKinsey Global Institute. (2014). A blueprint for addressing the global affordable housing challenge.

Tosun, yeşim & Şahin, Remzi. (2019). DEVELOPMENTS OF 3D CONCRETE PRINTING PROCESS.

Weinstein, D., & Nawara, P. (2015). *Determining the Applicability of 3D Concrete Construction (Contour Crafting) of Low-Income Houses in Select Countries*.

World Economic Forum. (2019). Making Affordable Housing a Reality in Cities.

Yeh, C. C., & Chen, Y. F. (2018). Critical success factors for adoption of 3D printing. Technological Forecasting and Social Change, 132(January), 209–216.

3D Printed Homes | Apis Cor | United States. (2019). Consulted on 13 december 2019.

Guion, L. A., Diehl, D. C., & McDonald, D. (2014). *Triangulation: Establishing the Validity of Qualitative Studies. Farhana Tabassum.*

R. Siebelink. (2013, September). THE ROAD AHEAD Business roadmapping and how to compensate for uncertainty: the case of the construction company.